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MINERALOGY

Mineralogy of the Kalkar quarry, Santa Cruz, California, by Eugene B. Gross, Charles W. Chesterman, Gail Dunning, and Joseph F. Cooper. Page 3

GEOCHEMISTRY

A test of chemical variability and field sampling methods, Lakeview Mountain Tonalite, Lakeview Mountains, southern California batholith, by A. K. Baird, D. B. McIntyre, E. E. Welday, and D. M. Morton. Page 11

STRATIGRAPHY

The effects of provenance and basin-edge topography on sedimentation in the basal Castaic Formation (upper Miocene, marine), Los Angeles County, California, by Robert J. Stanton, Jr. Page 21

Sedimentary rocks of late Precambrian and Cambrian age in the southern Salt Spring Hills, southeastern Death Valley, California, by Bennie W. Troxel. Page 33

GENERAL GEOLOGY

Reconnaissance geology of the Helena quadrangle, Trinity County, California, by Dennis P. Cox. Page 43

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SHORT CONTRIBUTIONS
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SPECIAL REPORT 92
California Division of Mines and Geology

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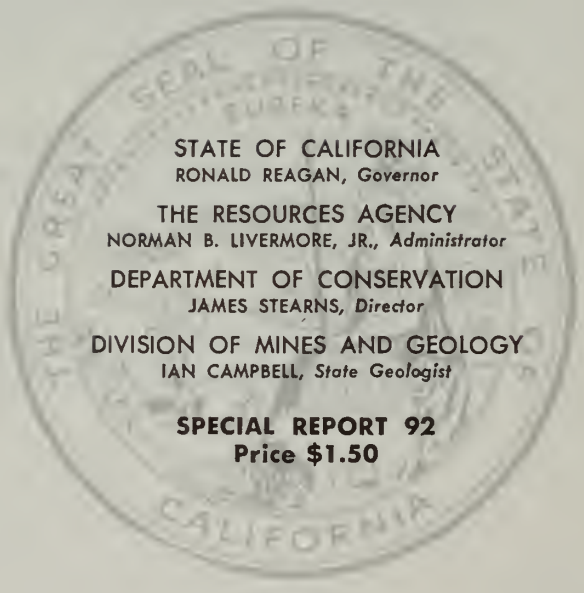

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SPECIAL REPORT 92
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MINERALOGY OF THE KALKAR QUARRY, SANTA CRUZ, CALIFORNIA*

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ABSTRACT

A suite of more thon 50 minerals hos been found in the Kalkar quorry of the Pocific Limestone Products Compony, neor Santa Cruz, Californio. Represented ore sulfides ond arsenides, sulfosolts, oxides, corbonotes, sulfates, phosphates, ontimonotes and silicotes. Sulfide, arsenide, ond sulfosolt minerolizotion is odjocent to foults ond in irregulor potches within medium- to fine-groined, recrystollized limestone. Interbeds of colc-silicote rocks contoin sulfides whereos the sulfosolts are confined principolly to the purer recrystollized limestones. Silicate minerols ore developed in the colc-silicote rocks. All secondary minerals are the result of neor-surfoce olterotion of the metallic minerols.

Porogenetic studies indicote on overlopping sequence of deposition of sulfides, orsenides, and sulfosolts. Molybdenite, coboltian laellingite, and gersdorffite formed eorliest at temperotures possibly over 600°C. Arsenopyrite, pyrrhotite, pyrite, and sphalerite crystallized next, perhaps below 550°C. The sulfosolts formed lost ot temperotures below 400°C. The minerolizotion may be reloted to the intrusion at depth of a Mesozoic (?) pluton of the Sur Series? (pre-Cretoceous).

The Pacific Limestone Products "Kalkar" quarry is in the southwest quarter of Sec. 11, T. 11 S., R. 2 W., M.D.M. at the west end of Spring Street in Santa Cruz (Photo 1). The earliest records of limestone quarry operations date back to before 1884 (Hanks, 1884). Fitch (1931, p. 8) noted occurrences of sulfides and arsenides in the recrystallized limestone beds of the quarry. Later in the 1930's, Fred W. Johnson, owner of the quarry, called to the attention of the late M. Vonson, an ardent amateur mineralogist, the rare and interesting minerals which were being uncovered during quarrying operations. Among the first unusual minerals to be identified were meneghinite and franckeite (Vonson, pers. comm., 1939). In the succeeding years, other unusual minerals were found in the quarry and the current list (1964) includes 50 minerals (Table 1). This interesting assemblage of minerals occurs in a massive recrystallized limestone which contains lenslike strata of calc-silicate rocks. The rocks probably belong to the Sur Series? of pre-Cretaceous age (Fitch, 1931, p. 2).

The purpose of this study was to investigate and to determine the paragenetic relations of a unique occurrence of sulfide and sulfosalt mineralization in a contact-metamorphic limestone deposit.

GEOLOGY

The quarry operation has been largely in poorly bedded to massive, recrystallized limestone with interbedded calc-silicate rocks. The beds, which are poorly defined, range in thickness from a few feet to several tens of feet. Generally, they are white in color, but zones of light to dark gray limestone and siltstone are common.

The size of the calcite crystals in the recrystallized limestone ranges from a tenth of an inch to an inch. Hydrogen sulfide is common in the limestone, and is especially noticeable as a fetid odor when the rock is freshly broken.

Lenticular interbedded layers of calc-silicate rock are most conspicuous in the southwestern part of the quarry where their thickness ranges from 5 feet to 35 feet. One such body, though faulted, is exposed also in the northern wall of the quarry where it gradually pinches out toward the east.

The fine-grained, greenish-gray to gray calc-silicate rock is moderately dense, and exhibits an indistinct foliation. The mineralogy of the calc-silicate rock is variable throughout the quarry, but in general, it consists principally of calcite and phlogopite with lesser amounts of tremolite, diopside, and forsterite, and minor amounts of actinolite, antigorite, sphene, graphite, and intermediate plagioclase (An_{65-70}).

* Presented orally at the Mineralogical Society of America meeting, Bozeman, Montana, July 1964.

Table 1. Minerals found in the Kalkar quarry, Santa Cruz, California.

Native Elements
- Graphite — C
- Bismuth — Bi

Sulfides and Arsenides
- Pyrite — FeS_2
- Sphalerite — ZnS
- Arsenopyrite — $FeAsS_2$
- Molybdenite — MoS_2
- Pyrrhotite — $Fe_{1-x}S$
- Cobaltian loellingite — $(Co,Fe)As_2$
- Gersdorffite — (Ni,Fe,Co)AsS
- Galena — PbS
- Chalcopyrite — $CuFeS_2$
- Covellite — CuS
- Greenockite — CdS
- Stannite — Cu_2FeSnS_4
- Stibnite — Sb_2S_3

Sulfosalts
- Franckeite — $Pb_5Sn_3Sb_2S_{14}$
- Meneghinite — $Pb_{13}Sb_7S_{23}$
- Jamesonite — $Pb_4FeSb_6S_{14}$
- Boulangerite — $Pb_5Sb_4S_{11}$
- Tetrahedrite — $(Cu,Fe)_{12}Sb_4S_{13}$

Oxy-Sulfide
- Kermesite — Sb_2S_2O

Oxides and Hydroxides
- Limonite — $Fe_2O_3 . nH_2O$
- Cassiterite — SnO_2
- Brucite — $Mg(OH)_2$

Carbonates
- Calcite — $CaCO_3$
- Aragonite — $CaCO_3$
- Azurite — $Cu_3(CO_3)_2(OH)_2$
- Malachite — $Cu_2CO_3(OH)_2$
- Witherite — $BaCO_3$
- Cerussite — $PbCO_3$

Sulfates
- Gypsum — $CaSO_4 . 2H_2O$
- Rozenite — $FeSO_4 . 4H_2O$
- Epsomite — $MgSO_4 . 7H_2O$

Phosphates, Arsenates and Antimonates
- Bindheimite — $Pb_{2-y}Sb_{2-x}(O,OH,H_2O)_{6-7}$
- Magnesian annabergite — $(Ni,Mg)_3(AsO_4)_2 . H_2O$
- Adamite — $Zn_2(OH)(AsO_4)$
- Fluorapatite — $Ca_5(PO_4)_3F$

Silicates
- Quartz — SiO_2
- Tremolite — $Ca_2Mg_5Si_8O_{22}(OH)_2$
- Phlogopite — $KMg_3AlSi_3O_{10}(OH)_2$
- Diopside — $CaMgSi_2O_6$
- Talc — $Mg_3Si_4O_{10}(OH)_2$
- Actinolite — $Ca_2(Mg,Fe)_5Si_8O_{22}(OH)_2$
- Chlorite — $(Mg,Fe,Al)_6(OH)_8(Si,Al)_4O_{10}$
- Sphene — $CaTiSiO_5$
- Forsterite — $(MgFe)_2SiO_4$
- Celsian — $BaAl_2Si_2O_8$
- Pabstite — $Ba(Sn_{.78}Ti_{.22})Si_3O_9$
- Taramellite — $Ba_4Fe^{2+}Fe_2^{3+}Ti(SiO_4)_{12}(OH)_4F$?
- Tourmaline — Complex silicate
- Biotite — $K_2(OH)_4(Mg,Fe,Al)_6(Si,Al)_8O_{20}$
- Antigorite — $Mg_6(OH)_8Si_4O_{10}$

NOTE: Minerals are arranged in classes and in order of decreasing abundance with the most common minerals at the top of headings.

The more massive, medium-grained siliceous layers show an abrupt textural change with the fine-grained calc-silicate rocks. These siliceous beds are less conspicuous in the quarry because their white to dull gray color blends well with the beds of recrystallized limestone. The siliceous type consists principally of calcite and quartz with lesser amounts of tremolite and diopside.

No granitic rocks were observed in the Kalkar quarry, but in a smaller quarry, about a tenth of a mile south, a narrow dike of altered coarse-grained quartz diorite occurs in fault contact with coarse-grained white recrystallized limestone. No mineralogical changes due to this dikelike body are apparent. According to Crawford (1894) a glaucophane schist interstratified with limestone underlies the south quarry. Rubble conceals the base of the two quarries at the present time.

Calc-silicate rocks similar to those exposed in the Kalkar quarry may be found also along Felton-Empire Grade near Bennett Creek and on Ice Cream Grade near Laguna Creek about 7 miles northwest of the Kalkar quarry. Rocks at those localities have been studied in detail by Leo (1967, in press). Although no fossils have been found in the limestone to date, Leo mapped the geology in the vicinity of the quarry and has included these rocks with the Sur Series (?).

MINERALOGY

In general, it is possible to classify the sulfide and sulfosalt minerals found at the Kalkar quarry on the basis of the type of rock in which they occur. The iron and arsenic sulfides are found in the siliceous limestones where they have replaced calcite grains. Sulfosalts are most prevalent as irregular fracture fillings within the medium- to fine-grained recrystallized limestone, although they also occur in the more quartzose calc-silicate rocks.

Meneghinite, admixed with boulangerite and jamesonite, is the principal sulfosalt. It is coarsely crystalline and frequently occurs in a semi-fibrous form, and is commonly found in veins and as isolated pods in the mineralized limestone (photo 2). Boulangerite and jamesonite have been identified as separate minerals by x-ray studies. In many places, where boulangerite occurs as fine fibrous masses, intermixed with tremolite, it resembles meneghinite. Jamesonite is common both in fresh and altered masses in limestone. In the altered state, it can be recognized by a yellow coating of secondary bindheimite. Rare, small crystals of cerussite have been found in vugs in the jamesonite.

Franckeite, although now much more difficult to find than any of the other sulfosalts, was at one time quite common. Good specimens of this mineral were obtained from the western part of the quarry, which has been inactive for many years. Recently, franckeite has been noted in small amounts at two separate lo-

Photo 1. General view to the north, Pacific Limestone Products quarry, Santa Cruz, California.

Photo 2. Meneghinite, $Pb_{13}Sb_7S_{23}$, showing twinning, × 2.5.

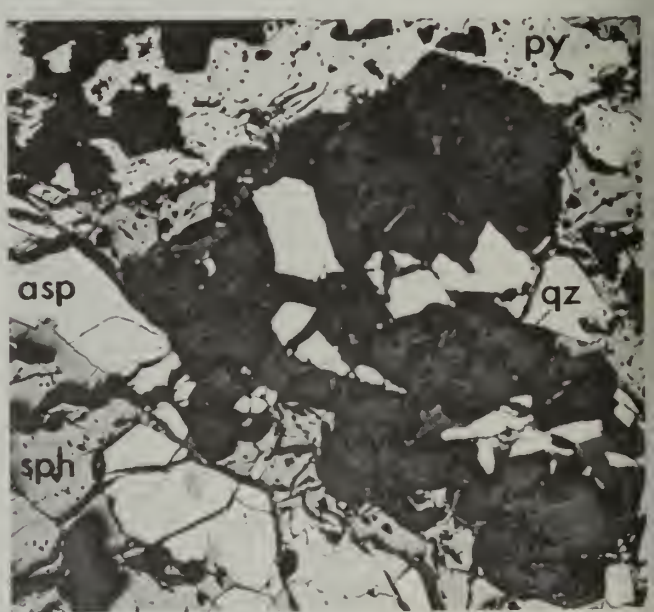
Photo 3. Fronckeite, $Pb_5Sn_3Sb_2S_{14}$, in limestone showing ploty habit and fine twinning, × 2.

calities in medium gray graphitic limestone where it occurs as thin, tabular, warped, striated crystals up to one inch in length (photo 3).

Sphalerite occurs in small pod-like masses in fine-grained limestone and as discrete crystals associated with pyrite and arsenopyrite in coarse-grained, white limestone (photo 4). The color of the sphalerite ranges from dark brown for separate crystals to black where it occurs in masses. Spectrographic analyses of the brown sphalerite indicate a trace of cadmium and iron, whereas analyses of the black sphalerite show a greater amount of cadmium, up to 1 percent, and a percent or more of iron. Cadmium is present also in the form of greenockite which occurs rarely as thin, pale yellow coatings on the black, massive sphalerite.

Pyrite, which is one of the commonest sulfide minerals in the Kalkar quarry, is present in the finer grained calc-silicate rocks as well as sparingly in the coarsely recrystallized, white limestone. Well-formed crystals of pyrite ranging in size from 1 mm to 1 cm have been found. Two distinct forms of pyrite appear in the deposit. Cubic crystals have been found in talc- and tremolite-bearing rocks, and crystals showing well-developed pyritohedral form are common in white, coarse-grained limestone. Pyrite also occurs massive as vein-like bodies traversing siliceous rock types, and as coatings of small crystals along shears in white limestone.

Photo 4. Photomicrograph showing white crystals of orsenopyrite (osp) included in quartz (qz) with pitted pyrite masses (py) and spholerite (sph), × 50.



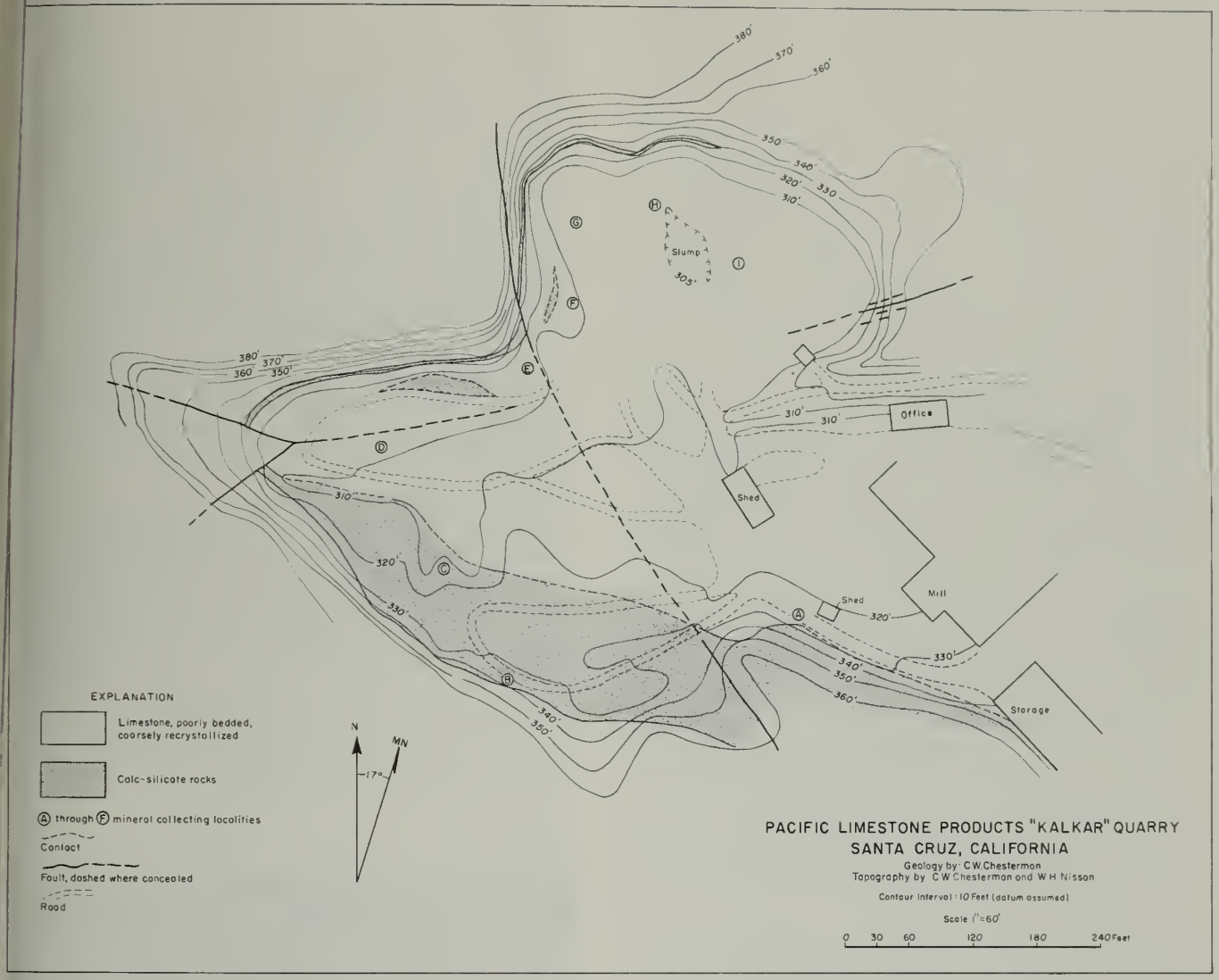


Figure 1.

MINERAL COLLECTING LOCALITIES

A
Adamite
Arsenopyrite
Goleno
Gypsum
Limonite
Molochite
Meneghinite
Pyrite
Rozenite
Sphalerite

B
Azurite
Bindheimite
Malochite
Meneghinite
Spholerite
Tetrahedrite

C
Actinolite
Arsenopyrite
Bindheimite
Boulongerite
Cerussite
Cholcopyrite
Fluoropotite
Franckeite
Galena
Jamesonite
Kermesite
Molochite
Meneghinite
Pyrite
Pyrrhotite
Stibnite
Tolc
Caboltian Loellingite
Tourmoline

D
Fluaropotite
Fronckeite
Meneghinite
Pyrite
Pyrrhotite
Sphalerite
Stannite

E
Boulangerite
Golena
Gypsum
Pobstite
Pyrite
Spholerite
Taramellite

F
Aragonite
Chlorite
Diapside
Forsterite
Meneghinite
Pobstite
Phlogopite
Pyrrhotite
Quortz, Amethyst
Sphalerite
Stibnite

G
Magnesion annobergite
Bindheimite
Gersdorffite
Greenockite
Jomesonite
Molybdenite
Pyrrhatite
Spholerite
Tremalite

H
Magnesion annobergite
Pyrite
Tolc
Sphalerite
Tremolite

I
Arsenopyrite
Gersdorffite
Meneghinite
Pyrite
Sphalerite
Talc

Arsenopyrite, like pyrite, also is a common mineral in the Kalkar quarry. Crystals up to several inches in length have been found in white recrystallized limestone. Arsenopyrite is a major constituent of narrow sulfide-quartz veins found in the recrystallized limestone and siliceous types. Pyrrhotite, which is not as common as pyrite and arsenopyrite, occurs mostly in the calc-silicate rocks in small masses associated with pyrite and sphalerite. Chalcopyrite is rare, and is commonly altered to azurite and malachite. Cobaltian loellingite has been rarely found, associated with masses of coarsely crystalline arsenopyrite. Tetrahedrite was noted in the quarry at only one locality, where it occurred in a small mass partly altered to azurite, malachite and bindheimite. Gersdorffite occurs sparingly in small grains enclosed in sphalerite and associated with molybdenite in veins which contain small crystals of magnesian annabergite.

Stibnite, exhibiting poorly formed prismatic crystals, minute grains or thin films, has been identified from two localities in the quarry. The stibnite is characteristically altered to reddish kermesite and yellowish bindheimite; both occur as thin coatings. Coarsely crystalline galena is commonly associated with quartz and taramellite. At a few places, especially in the limestone, the galena has been altered in part to cerussite.

Covellite and stannite are very rare minerals in the Kalkar quarry. The covellite occurs as a thin coating on fractures in chalcopyrite from which it was derived. Although stannite has not been found in recent years, rare crystals were observed in close association with meneghinite and native bismuth in a fine-grained graphitic limestone in the western part of the quarry.

Cobalt-bearing loellingite and stannite have required x-ray identification. These two minerals are rarely found in small bodies of massive sulfides that include pyrite, pyrrhotite, gersdorffite, and arsenopyrite in calc-silicate rocks, or in small patches of coarsely recrystallized limestone.

The silicate gangue minerals that constitute a bulk of the noncarbonate minerals have a wide range in composition and types as is shown in Table 1. Many of these minerals can be recognized easily in hand specimen, whereas others occur in small crystals which lend themselves best to identification under the petrographic microscope or by x-ray diffraction methods.

Quartz is common and has two distinct modes of occurrence, (1) as an original constituent of calc-silicate rocks, and (2) with tremolite and pyrite in veinlets cutting the recrystallized limestone and calc-silicate rocks. Where the quartz occurs as a constituent of the calc-silicate rocks, it is in xenoblastic grains and may constitute up to 40 percent of the rock. The quartz in the veinlets is a very fine-grained, gray rock that resembles porcelain. Several specimens of amethyst quartz with pale purple crystals up to ⅛ inch in length were collected from a fracture in the siliceous limestone.

Tremolite, ranging from white to colorless, is exceedingly common and is especially abundant in some of the purer recrystallized limestones where it occurs in prismatic crystals as much as several inches in length. Actinolite, which is less common than tremolite, occurs in the calc-silicates where iron sulfides are abundant. A variety of tremolite called mountain leather can be found along fractures in sheared and faulted limestones.

The micas present include phlogopite, chlorite, and biotite. Abundant phlogopite occurs in pale pinkish-brown to colorless plates in the recrystallized limestone which, in places, shows a well-developed foliation. Chlorite is pale green and generally is associated with phlogopite and pyrite. Rarely a few flakes of biotite were found in the calc-silicate rocks that contained an abundance of arsenopyrite and pyrite.

Diopside and forsterite are less common than tremolite and phlogopite. The diopside and forsterite occur as colorless, xenoblastic grains in recrystallized limestone. At a few places in the quarry narrow zones of a dark-gray, medium-grained recrystallized limestone, ranging from a few inches to a foot thick, contain principally calcite, forsterite, and graphite. The forsterite is altered in part to pale greenish antigorite and white to light green talc.

Dark brownish-black masses of taramellite, showing cleavage planes containing tremolite, appear rarely in siliceous rocks of the quarry. Other barium-bearing minerals include witherite, celsian, and the recently described mineral, pabstite, (Gross, Wainright, and Evans, 1965). The witherite, which is exceedingly rare, has been found very closely associated with pabstite within a medium-grained siliceous limestone along with tremolite, quartz and galena. Pabstite is white with a delicate pink tinge. It is extremely difficult to identify in hand specimens, except by its bluish-white fluorescence under ultra violet light (photo 5). Celsian is also very scarce, but where present is in small crystals in the siliceous rock types.

Photo 5. Pabstite (pst) in matrix composed of quartz (qz) and taramellite (tm) under short wave ultraviolet light, × 1.5.

Small amounts of fluorapatite occur in the quarry, s aggregates of yellow-brown xenoblastic grains in nassive pyrrhotite, and as small prismatic, brown crys- als in quartz. Sphene is not uncommon, generally in enoblastic, brown grains in the calc-silicate rocks. Tourmaline occurs in small, green, prismatic crystals orming a sunburst pattern in graphitic limestone.

Oxide minerals are rare in the quarry, but a few mall, honey-yellow crystals of cassiterite were found ssociated with taramellite and pabstite in siliceous imestone. Brucite was found as a minor constituent long with diopside and forsterite in a thin layer of ecrystallized limestone between more massive layers of calc-silicates. The brucite is in white, rounded grains which are visible only under the petrographic microscope.

Near-surface alteration of the sulfides, sulfosalts, and arsenides has produced limonite, white coatings of rozenite, gypsum and epsomite, and green encrusta- ions of magnesian-annabergite, adamite, malachite, nd azurite.

Of these secondary minerals, particular mention hould be made of the rozenite which heretofore has been identified from only one or two other localities n California. The rozenite at the Kalkar quarry oc- curs on fractures in broken and sheared siliceous lime- stone that is rich in arsenopyrite. Its identification has been confirmed by x-ray diffraction methods.

Adamite, in small, pale green crystals, occurs with rozenite. Gypsum, which is one of the commonest secondary minerals, is especially noticeable along frac- tures in pyrite-bearing calc-silicate rocks. Epsomite is found sparingly only during periods of extreme dry- ness as feathery encrustations on fractures in magne- sium-rich rocks.

In addition to calcite which is the main constituent of the recrystallized limestones, good crystals of sec- ondary calcite showing columnar and rhombohedral forms occur at several places in the quarry, especially near and in fault zones. Aragonite occurs as delicate glassy crystals lining cavities in the recrystallized lime- stone.

Azurite and malachite are formed as the result of alteration of tetrahedrite and chalcopyrite. The azur- ite, which is rarer than malachite, appears in small, well-formed crystals on tetrahedrite. Malachite occurs only as thin velvety green crusts on tetrahedrite and chalcopyrite.

Cerussite occurs as brilliant, glassy cystals in cavi- ties in galena and as isolated glassy crystals in bind- heimite. Small, pale apple-green crystals of magnesian annabergite encrust fractures in siliceous limestone that contains gersdorffite. Some magnesian annabergite from the quarry contained zinc as determined by emission spectrographic analysis.

TEMPERATURE OF FORMATION

The sulfide mineral assemblages at the Kalkar quarry that indicate temperature of formation include: pyrite- sphalerite-pyrrhotite, arsenopyrite-pyrrhotite-pyrite, and pyrite-pyrrhotite. The temperatures indicated by these assemblages were compared with values ascer- tained for non-metallic mineral assemblages, forsterite- diopside-calcite, calcite-tremolite (Barth, 1952, pp. 288–289), calcite-wollastonite and the presence of graphite.

The methods used to determine temperature of for- mation required x-ray diffraction spacings and cell edge calculations of $d\text{Å}_{(111)}$ sphalerite, $d\text{Å}_{(131)}$ arseno- pyrite, and $d\text{Å}_{(102)}$ of pyrrhotite with use of an ap- propriate internal standard of quartz or fluorite for d-spacing correction. The measured values for pyr- rhotite were plotted on the charts given by Arnold (1956, 1958); for sphalerite on the charts of Barton and Kullerud (1958) and Skinner, Barton, and Kul- lerud (1959); and for arsenopyrite on the charts by Clark (1958, 1960). Stability ranges, according to these investigators, include: molybdenite unstable above 1350°C.; pyrite unstable above 743°C.; arseno- pyrite unstable above 720°C.; loellingite unstable be- low 670°C.; pyrrhotite unstable above 610°C.; wol- lastonite formed at 700°C.; graphite formed at 550°C.; sphalerite stable from 138° to 894°C.

Stability ranges of mineral combinations include: arsenopyrite-pyrite stable below 491°C.; arsenopyrite- pyrite-pyrrhotite stable below 491°C.—with applied pressure below 510°C.; arsenopyrite-pyrrhotite + liq- uid stable below 702°C.; arsenopyrite to pyrrhotite- loellingite + liquid stable at 670°C.; pyrite-pyrrho- tite stable below 700°C.; pyrite-pyrrhotite-molybde- nite + liquid + vapor stable below 726°C.; pyrite- pyrrhotite-hematite stable between 675° and 700°C.; pyrite-pyrrhotite-sphalerite stable between 500° and 600°C.; pyrrhotite-molybdenite stable above 726°C.; pyrrhotite-pyrite-chalcopyrite stable below 550°C.; and pyrrhotite-sphalerite stable between 500° and 600°C.

The pyrrhotite samples in this deposit have values of $d\text{Å} = 2.065 = 47.3$ mol % Fe and $d\text{Å} = 2.068 = 47.56$ mol % Fe; these data indicate a temperature above 300°C. but do not indicate an upper limit. How- ever, the pyrrhotite occurs with chalcopyrite and py- rite, suggesting a value below 550°C. Sphalerite gave a value of $d\text{Å} = 5.41769 = 18.6\%$ FeS, hence a range of temperature of 550° to 670°C. Arsenopyrite indi- cated a value of $d\text{Å} = 1.6336$, hence a temperature of 547°C. at less than one bar pressure, or about 525°C. at 1000 bars pressure.

Arsenopyrite and sphalerite are the most abundant sulfides in the deposit except for pyrite. On the other hand, the high temperature indicators pyrrhotite, loel- lingite, and gersdorffite, are relatively scarce. This would suggest a lower temperature of formation for the sulfides of the deposit, i.e. below 600°C. The non- metallic mineral assemblages of forsterite-diopside-cal- cite (step seven of Bowen's progressive metamorphism of a siliceous limestone and dolomite; Ingerson, 1955) would indicate a temperature range of 550° to 750°C. at 0 to 300 atmospheres pressure. Bowen's wollaston- ite-calcite curve would appear at 700°C.—step ten— but no wollastonite has been identified from the de- posit. At atmospheric pressure calcite + quartz may form wollastonite + CO_2 at 400°C. under special physical-chemical conditions. According to Ingerson (1955), Winchell states that graphite may form at 550°C.

According to Lindgren (1933, p. 707), "the succession of the sulfides (in a pyrometasomatic deposit) generally begins with arsenopyrite and pyrite; then follow pyrrhotite, molybdenite, sphalerite, chalcopyrite, galena; the rarer sulphosalts were formed last." The sulfosalts which are fairly common at the Kalkar quarry probably formed at temperatures below 400°C. Robinson (1948) synthesized the lead sulfantimonite, boulangerite, and other lead antimony sulfides from alkaline solutions at 425°C. In the Coeur d'Alene district, Idaho, Waldschmidt (1920) stated that sulfosalts can be formed by post mineral processes between 50° and 100° C. with applied pressure. He found that tetrahedrite reacted with galena to produce boulangerite and jamesonite. He concluded that lead sulfantimonites might form in the late stages of hypogene vein formation, during differential pressure and deformation of primary veins containing lead and antimony, or in states of oxidation where oxygen concentration is low.

PARAGENESIS

A few of the sulfides at the Kalkar quarry show paragenetic relationships. Arsenopyrite is included in massive sphalerite which in turn contains small veinlets of chalcopyrite and pyrite. Sulfosalts border the iron sulfides and may fill fractures in non-metallic minerals.

Because of the spotty nature of occurrences of ore minerals at the Kalkar quarry, a paragenetic sequence is difficult to decipher. One concludes that an overlapping sequence of deposition occurred, with molybdenite, loellingite, and gersdorffite formed earliest at temperatures possibly above 600°C. Later arsenopyrite, pyrrhotite, pyrite and sphalerite developed, perhaps below 550°C. Lastly the sulfosalts formed below 400°C.

CONCLUSION

From field and laboratory studies, it appears that the mineralization of the Kalkar quarry was as follows: 1) recrystallization in the limestone and formation of forsterite, diopside, and phlogopite in the calc-silicate rocks, 2) formation of sulfides and sulfosalts related to metasomatism following metamorphism, probably at temperatures below 550°C., and 3) the near-surface oxidation of the sulfides and sulfosalts, which has been accelerated in areas adjacent to the faults in the quarry. It is believed that the mineralization at the Kalkar quarry was the result of the emplacement of a plutonic body.

ACKNOWLEDGMENTS

Mineral specimens donated for study by Charles Milton of the U. S. Geological Survey greatly aided the project. The authors also appreciate the field assistance of the late William Nisson and his interest in the mineralogy of the Kalkar quarry.

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A TEST OF CHEMICAL VARIABILITY AND FIELD SAMPLING METHODS, LAKEVIEW MOUNTAIN TONALITE, LAKEVIEW MOUNTAINS, SOUTHERN CALIFORNIA BATHOLITH

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ABSTRACT

The Lakeview Mountain Tanalite is part af the bathalith af southern California; it is exposed over an area of 21 squore miles in the Lakeview Mountoins, Riverside County. This poper describes a preliminary investigotion which supplies the dato required for the design af a sampling plan adequote for mapping the relative amounts af the major and minor chemical elements.

Specimens were collected both by diamand drill and by hommer and a tatal of 174 rock powders were anolyzed in duplicate for Na, Mg, Al, Si, K, Co, Ti, and Fe by X-roy fluarescence. Statistical analysis of the results indicates that care segments as small as 3 inches in length and 7/8 inch in diometer are adequate specimens of rock for the quantitative determination af mojor and minor elements. Relotively high chemical variability between specimens callected 5 feet aport implies that regionol mopping of the chemistry is not possible unless combined somples are used ta represent each grid paint.

Evaluation of geochemical distributions over heterogeneous plutonic assemblages like the southern California batholith requires considerable knowledge of the chemical variability within the individual rock bodies. To obtain such information, detailed geologic mapping, planned sampling, and precise chemical analyses are needed.

Two areas in the San Bernardino Mountains have been studied in this way (see figure 1 for locations). The first was Rattlesnake Mountain pluton where seven rock units were studied, a structural analysis made, and more than 900 major-element chemical analyses completed (MacColl, 1964; Baird, et al., 1964). The second is the type locality of the Cactus Quartz Monzonite where abundant information on the chemistry of the principal rock unit was obtained (Richmond, 1965) although the geographic extent of the sampling was limited.

A similar investigation of another area is reported here. This is the Lakeview Mountains on the Perris plain southeast of Riverside (figure 1). The Lakeview Mountain Tonalite (Larsen, 1948, p. 57) and the surrounding metamorphic and plutonic rocks are well exposed and have been mapped in detail by D. M. Morton (manuscript in preparation). The present report summarizes the results of a preliminary study of the distributions of major and minor elements (Na, Mg, Al, Si, K, Ca, Ti, and Fe) in the Lakeview Mountain Tonalite in the southern part of the Lakeview Mountains (figure 2). The ultimate goal is to determine whether the distributions of chemical elements can be correlated with the structure, and thus to provide information on the origin of the body; but a

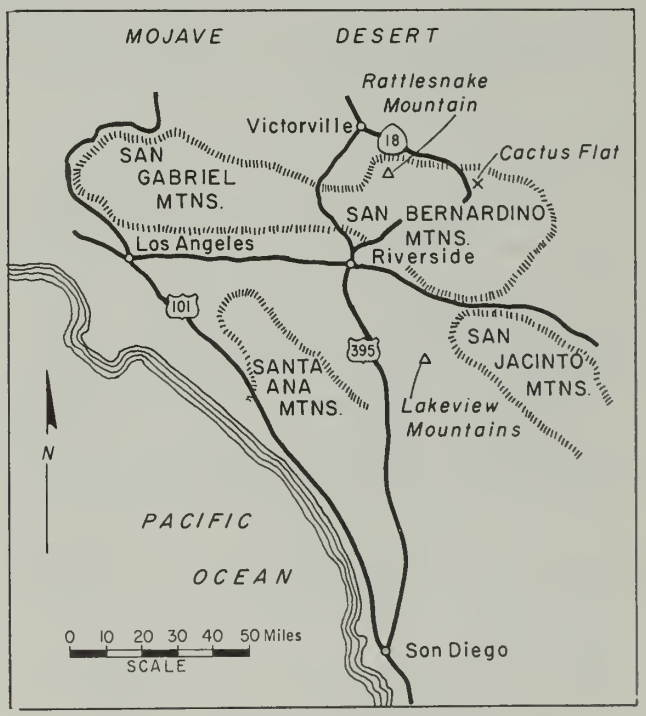

Figure 1. Index mop of locolities discussed in the text.

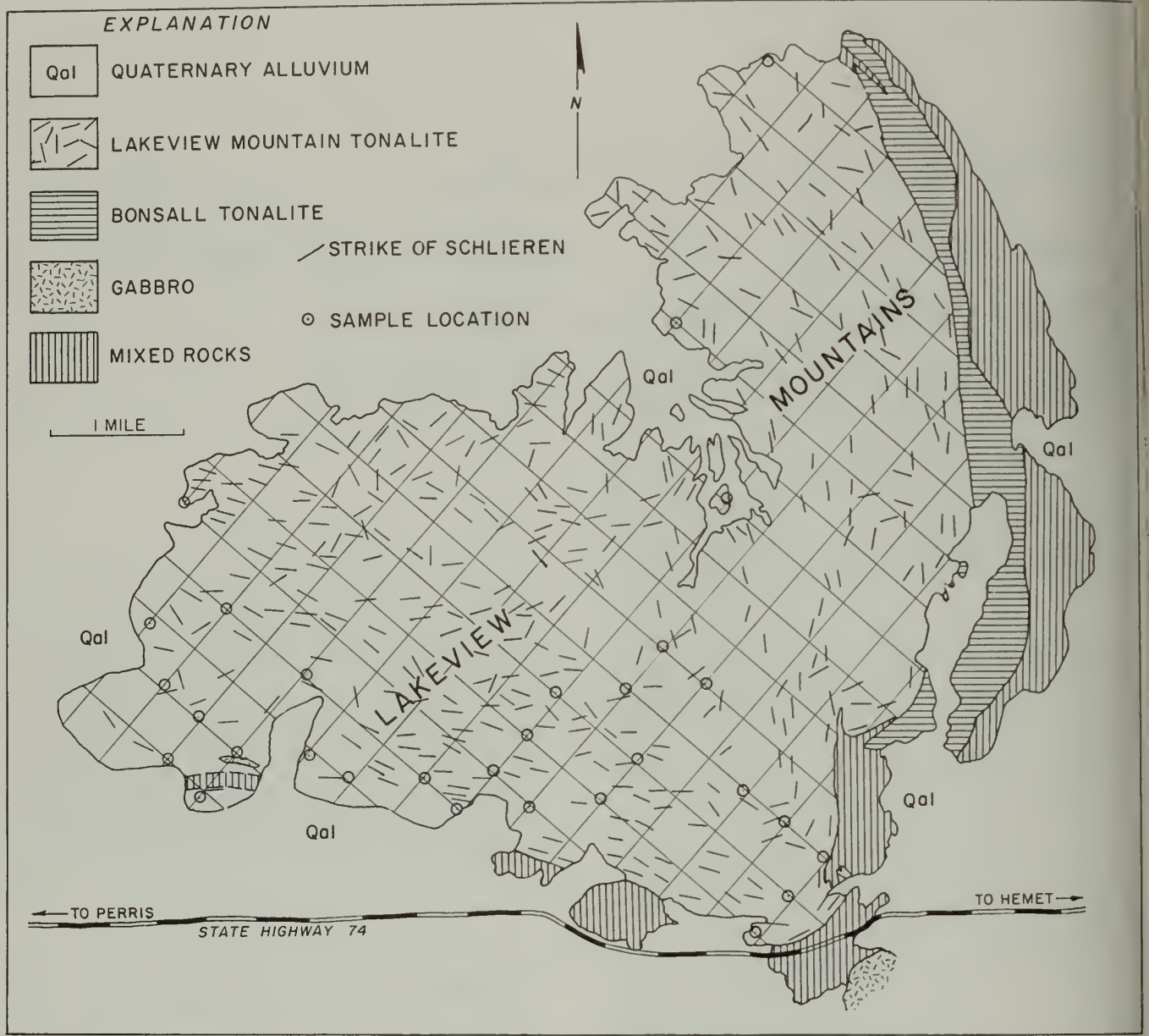

Figure 2. Generalized gealagic map af the Lakeview Mauntains, Riverside Caunty, California, showing distributians of major rock types, strikes af steeply dipping schlieren, sample callectian grid and sample locatians.

pilot study was needed so that an adequate sampling plan could be designed for the whole pluton.

The two previous studies in the San Bernardino Mountains have shown the importance of determining rock variability on at least two scales. The variance between localities distributed hundreds or thousands of feet apart can be determined only if the variance within each locality, measuring a few square feet, is known. If each outcrop within a pluton is modally and chemically heterogeneous, it may be impossible to demonstrate regional variations over the extent of the pluton unless several rock specimens are collected at each locality.

The tests described in this paper were designed to provide estimates of the following with respect to the major and minor elements:

1) the required minimum volume af single specimens ta assure that these are representative rocks and nat merely fragments af ane or more minerals;
2) the chemical variability af specimens from a single autcrop with continuaus expasure aver at least 5 feet;
3) the chemical variability af specimens fram different autcraps 300 hundred feet apart;
4) the chemical variation and mean compasitian af the Lakeview Mauntain Tanalite aver 10 square miles af expasure in the sauthern part af the bady.

Standard statistical terminology is used throughout the paper. Definitions of the terms used most frequently are appended but a detailed exposition of the procedures is beyond the scope of this report. Many introductory statistical texts are now available and the reader is referred to the literature cited.

Photo 1. Brood felsic schlieren (left) ond mofic inclusians (right) in Lakeview Mountoin Tonolite.

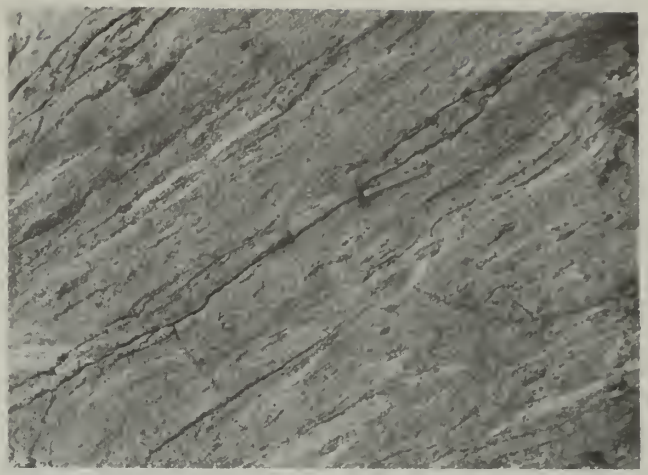

Photo 2. Thin felsic and mafic schlieren ond oriented inclusions in the Lokeview Mountoin Tonalite.

Acknowledgments. We thank the National Science Foundation for their financial support (grant GP-1336, to Baird and McIntyre) and the California Division of Mines and Geology for their cooperation in the research.

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RÉSUMÉ OF THE GEOLOGY OF LAKEVIEW MOUNTAINS

The tonalite of the Lakeview Mountains was first described by Dudley (1935, p. 502) as "Lakeview quartz-hornblende diorite." On the basis of similar lithology, Merriam (1941, p. 366; 1946, p. 247) equated a tonalite in the Ramona quadrangle, San Diego County, with the rock described by Dudley. Larsen (1948, p. 57) revised the name to Lakeview Mountain Tonalite and further extended its usage to other bodies in the batholith of southern California. Typically the tonalite is medium- to coarse-grained and consists of about 60 percent andesine and 20 percent quartz, with about 20 percent of hornblende and biotite. Hornblende is usually more abundant than biotite.

In this area the Lakeview Mountain Tonalite has a pear-shaped outline on the map and its long axis trends west-northwest. Apparently its walls are steep. Exposures of fresh rocks abound despite the low relief and the extensively developed erosion surfaces.

To the east, the pluton is rimmed by a thin, arcuate body of tonalite of similar appearance; this is the Bonsall Tonalite of Larsen. Along the southern edge of the pluton there is a complex mixture of tonalite and metasedimentary rocks. The pluton is covered by alluvium along the north and west edge of the mountains.

Schlieren * are the most characteristic structural features of the tonalite (photos 1 and 2). Most are planar, steeply dipping, and range in thickness from less than 1 inch to several feet. Locally, alternating light and dark schlieren give rise to a strikingly banded rock. Less common are wispy schlieren; folded schlieren are present, but rare. The schlieren range in composition from felsic (quartz-feldspar) to totally mafic (hornblende-biotite).

Geometrical analysis of the schlieren has defined three orientation groups (figure 2): one group is parallel to the margins of the pluton; the other two trend northeast and northwest respectively. In all other aspects these schlieren groups appear to be similar.

COLLECTION AND ANALYSIS OF SAMPLES

The results of previous studies in the San Bernardino Mountains suggested that a sampling grid with localities spaced about 2000 feet apart might be appropriate for a preliminary geochemical test in the Lakeview Mountain Tonalite. This spacing would provide 150 control points for future studies of elemental variations over the whole pluton if the results from the preliminary tests showed such a plan to be feasible. This grid is shown in figure 2.

For the preliminary tests reported in this paper, 30 of the 150 grid points were selected, primarily for their accessibility. Most are in the southern part of the body. For economic reasons a fully random selection of collecting localities was not used in this pilot study. These procedures of sampling were followed:

a) A single 2000 to 3000 gram specimen wos collected with a sledge hammer at the outcrap closest ta each selected grid paint. These locotions (hereofter termed *localities*) are shown in figure 2.

b) 5 feet from this hammered specimen a ⅞ inch diameter rock care, greater thon 12 inches long, was obtained by diomond drilling. At twa af the localities no care could be obtained ond a second specimen was collected with the hammer. Twa specimens 5 feet apart are taken as representing an outcrop.

c) 300 feet away, in a predetermined direction, a single 2000- to 3000-gram specimen was collected with the sledge hammer. Twa specimens 300 feet apart are taken as representing a subarea.

* Schlieren ". . . may be said to be tabular, disk-like rock bodies, composed essentially of those minerals that build up the surrounding rocks, but in different proportions . . . Synonyms are 'foliation' and 'fluxion banding'" (Balk, 1937, p. 15).

To determine the minimum volume of rock needed for individual specimens the cores were first cut into segments. Beginning at the top of each core two 3-inch and one 6-inch segment were obtained in sequence. Each segment was crushed, pulverized and split. A split of each of the two 3-inch segments was recombined to provide a single sample representative of the upper 6 inches of the core. This operation of splitting and recombining resulted in samples representing two 3-inch cores and two 6-inch cores. The mean composition of the two 6-inch cores is equivalent to the mean of two analyses of one 12-inch core. Each of the hammered specimens was crushed, pulverized and split to about 40 grams and then fine-ground in a Pica Mill.

After fine-grinding, all samples were split and specimens for X-ray analysis were prepared following standard procedures (Welday, et al., 1964). X-ray methods (Baird, et al., 1963) were used to analyze for Na, Mg, Al, Si, K, Ca, Ti, and Fe in each of 174 specimens, as follows:

From each of 28 localities, one specimen collected by hammer, one 12-inch core (divided into two 3-inch segments and one 6-inch segment), and also one specimen collected by hammer at a distance of 300 feet. From each of two additional localities, where cores could not be obtained, two specimens were collected by hammer at an interval of 5 feet and a third specimen was collected at a distance of 300 feet. Two briquettes were prepared from each of the 174 specimens and all were analyzed for eight elements. The purpose of replication is to ensure that any gross errors in preparation and analysis will be detected and to evaluate overall analytical precision. No gross errors were found. The result is 2784 elemental determinations. Calibration against standards and quality control of the analyses were performed by computer techniques (McIntyre, 1964).

PRECISION OF ANALYSES

Eight elements were determined, and two analyses were made independently for each of 174 rock powders. The resulting 348 values for a given element vary for two quite different reasons: 1) the rock powders have different compositions, and 2) the analytical techniques are not perfectly reproducible. If a single powder had been analyzed many times the precision of the analyses could have been given as the standard deviation of the replicate determinations. But this procedure is not practical here; instead we extract a pooled value for the precision by algebraic means.

If the data are arranged as an array consisting of two columns (two briquettes/specimen) and 174 rows (the specimens), then clearly one would expect to find more variance between rows (powders of different rocks) than within rows (powders of the same rock). This is a simple application of the well known technique of Analysis of Variance (cf. Dixon and Massey, 1957; Crow, et al., 1960) and it constitutes a one-way, or one-factor, layout with replications. In the present instance the differences between the rocks constitute a factor which we eliminate mathematically. The results are given in Table 1. Because each of our reported analyses is the mean of two determinations, the effective precision is thereby improved and it is this value that is quoted. The analytical precision measures the basic errors to which all chemical variability, due to inherent geologic differences between the rocks, must be compared.

MINIMUM SAMPLE VOLUME AND THE INFLUENCE OF GRAIN SIZE

Collection of rock specimens for quantitative analysis requires that an adequate volume be obtained so that all mineral phases in the rock are present in the sample and closely approach their true proportions. Homogeneity is often a function of scale and a specimen that is too small will not be a representative sample. In some rocks the grain size is the critical control on required volume, but in banded or layered rocks, grain size may not be the most important factor.

Our data permit the following comparisons of chemical variability between different volumes of Lakeview Mountain Tonalite:

1) Comparisons, for each of 28 cores, between compositions of the top 3 inches and the top 6 inches.
2) Similar comparisons between the top 6 inches and the entire 12-inch core.
3) Comparisons between the 12-inch cores and the 2000–3000 gram specimens collected by hammer.
4) Comparisons between the standard deviations of 3-inch core segments within 6-inch cores, and 6-inch core segments within 12-inch cores.

Table 2A shows that the mean composition determined by analysis of 2000–3000 gram specimens is not significantly different from that determined from analysis of 3-inch core segments. The greatest differences in means are between the sets of 2000–3000 gram specimens collected with a hammer. It should be emphasized that in comparison to the cores the large samples were inconvenient to handle; they required cleaving before they could be introduced into the crusher. The necessary splitting of large samples, and then their recombining after pulverizing, not only add to preparation time, but may introduce additional errors.

Table 2B provides a comparison between the standard deviations of 3-inch and 6-inch core segments. The values given result from a one-way Analysis of Variance. Even although the mean composition can be determined just as well from 3-inch cores as from large specimens, it could still be that the 3-inch segments were more variable. However Table 2B shows that Ti is the only element with a significant improvement in the standard deviation associated with 6-inch as compared with 3-inch segments. Despite this fact, it appears that 3-inch cores would be satisfactory for mapping Ti in the Lakeview Mountain Tonalite. This statement is made because of the following results of an Analysis of Variance: *

* The amount of Ti in neighboring 3-inch segments is expected to vary because Ti is the least abundant of the elements determined and it is probably contained largely in accessory minerals, such as ilmenite and sphene. The data presented indicate that the inhomogeneity effects associated with 3-inch segments are random.

	Components of standard deviation	
	between cores	between segments within cores
28 cores, each with		
a) two 3-inch segments	.046	.036
b) two 6-inch segments	.044	.022

We conclude that individual core segments as small as 3 inches in length and ⅞ inch in diameter are adequate for major element determinations. These cores weigh only about 40 grams, and specimens ten times as large are easily collected and convenient to prepare.

Grain size rather than layering appears to be the major factor controlling the minimum specimen size for chemical studies of the Lakeview Mountain Tonalite. The schlieren contribute to chemical variability on the scale of outcrops, not hand specimens. In order that data can be accumulated to assess the relationship between grain size and required specimen size in plutonic igneous rocks, the coarseness index (Chayes, 1956) of the Lakeview Mountain Tonalite has been estimated. The index measure is the number of changes of major-mineral identity in a 25 mm traverse of a thin section. Rocks from nine localities scattered over the Lakeview Mountains have indices ranging from 15 to 28; the mean is 22.

The only other rock that we know to have been tested for minimum specimen size is the porphyritic biotite quartz monzonite of Rattlesnake Mountain pluton (Baird, et al., 1964). This rock is more massive and less layered than the Lakeview Mountain Tonalite and it has a coarseness index of 11 to 23, with a mean of 16. For the determination of major elements the minimum specimen size is between 6 and 12 inches of ⅞-inch diameter core.

COMPARISON BETWEEN CORES AND HAMMERED SPECIMENS

At 28 localities a core and a hammered specimen were collected five feet apart, and for the eight elements in turn the difference between each core and its paired specimen was found. If the cores and hammered specimens are equally satisfactory samples of the rock, we would expect the mean difference to be zero for each element, and for the numbers of positive and negative differences to be balanced. The following table summarizes the non-zero differences found by subtracting the analysis of each hammered specimen from that of the corresponding core. No significant difference between the two modes of collecting can be detected at the 95 percent confidence level for any one of the elements analyzed (cf Crow, et al., 1960, p. 56).

	+	−
Na	17	11
Mg	15	13
Al	11	17
Si	11	17
K	13	15
Ca	18	10
Ti	12	13
Fe	12	16

VARIABILITY OF THE ROCKS ON DIFFERENT SCALES

Because two specimens were collected 5 feet apart at each of 30 localities, Analysis of Variance makes it possible to isolate a pooled estimate of the variance for each element within outcrops. In a similar way the pair of hammered specimens collected 300 feet apart is a sample of a subarea, and, because there are 30 such pairs, the total variance for each element can be partitioned into one component due to variation between subareas, and another which is a pooled measure of the variance between the different outcrops within a subarea.

The results, given in Table 1, show the contributions to total variability for each sampling scale. It should be noted that standard deviations are not additive; if the total variance at any scale is required it is computed by summing the squares of the standard deviations at this scale and all lower levels in the logical hierarchy.

The last column of Table 1 shows the mean elemental composition of the sampled part of the Lakeview Mountain Tonalite. Within the ± ranges given, the values are those expected 95 times out of a hundred if this sampling and analysis scheme were to be repeated.

Chemical mapping is possible only if regional variation can be detected above the local chemical variability, or compositional "noise", on smaller scales. It is clear from Table 1 that variabilities on the scales of outcrop and subarea often are large compared with the components of variability estimated over 10 square miles of the pluton. Hence meaningful maps of elemental distributions can be obtained only by collection of several specimens per locality, by the inclusion of several localities per subarea, or both. Because uncorrelated variances are additive and standard deviations are not, it follows that the scale with the largest component of standard deviation will predominate overwhelmingly. This fact of arithmetic, summarized

Table 1. Lakeview Mountain Tonalite: Summary of chemical composition and components of variability on different scales.

Element	Analytical precision[1] (s in wt%)	Variability of rocks within an outcrop[2] (s in wt%)	Variability of outcrops within a subarea[3] (s in wt%)	Variability of subareas over 10 sq. mi.[3] (s in wt%)	Composition over 10 sq. mi.[3] (x in wt% ± 2s)
Na	0.04	0.17	N.S.	N.S.	2.33± .05
Mg	0.04	0.24	0.24	0.38	1.99± .16
Al	0.06	0.34	0.35	N.S.	8.99± .13
Si	0.09	0.32	N.S.	0.85	27.6(6)± .32
K	0.01	0.20	N.S.	0.29	1.13± .12
Ca	0.02	0.23	N.S.	0.53	4.75± .20
Ti	0.003	0.030	0.052	N.S.	0.48± .015
Fe	0.04	0.47	0.64	N.S.	5.17± .18
Degrees of freedom	174	30	30	29	

N.S. = not significant at 95% confidence.
[1] Based on 2 determinations per specimen.
[2] 30 outcrops each with two specimens 5 feet apart.
[3] 30 subareas each with two specimens 300 feet apart.

in the following formula, should be taken into account in planning future sampling.

$$s_s^2 = \frac{s_a^2}{n_a n_r n_o} + \frac{s_r^2}{n_r n_o} + \frac{s_o^2}{n_o}$$

Where s_s^2 is effective variance, for a given element, within subareas

s_a^2 is analytical variance based on 1 determination per specimen, and n_a is the actual number of determinations per specimen.

s_r^2 is variance of rocks within an outcrop, and n_r is number of rock specimens collected per outcrop.

s_o^2 is variance of outcrops within a subarea, and n_o is number of outcrops sampled per subarea.

A geochemical pattern over many subareas can be obtained only if subareas can be distinguished from one another; i.e. s_s^2 must be kept relatively small. This can be achieved by increasing n_r and n_o. The analytical variances are small, and therefore many rock specimens per outcrop or subarea can be combined for a single chemical analysis (i.e. $s_a^2/n_a n_r n_o$ reduces to s_a^2/n_a). Because each specimen serves for all the elements that are to be determined, those elements which are most variable, or most important for a particular study, will control the optimum method of collecting.

REGIONAL PATTERNS OF CHEMICAL VARIABILITY

As shown in Table 1 there are significant components of standard deviation on the scale of 10 square miles for the elements Mg, Si, K, Ca. Before more extensive sampling is done over the whole of the Lakeview Mountain Tonalite in the Lakeview Mountains, it is important to determine whether or not these large scale variations are regularly distributed or merely random. Several authors (e.g. Krumbein, 1959) have shown that mapped data can often be represented satisfactorily by polynomials fitted by the least squares criterion. The method is termed "trend surface analysis" (Grant, 1957) and is a direct extension to three dimensions of time-trend graphs in two dimensions. In trend surface analysis the independent variables are the geographic coordinates of each locality; the mean elemental value at that locality is treated as the dependent variable. Surfaces of increasing complexity can be computed and their statistical significance tested. It is also possible to determine how much of the total information is explained by a particular surface; the measure is one minus the ratio of the sum of squares of the residuals to the total sum of squares.

Trend surfaces were computed (McIntyre, 1963) for the thirty localities in the southern part of the Lakeview Mountains. Statistically significant * surfaces were obtained for K, Ca, Mg, and Al (figure 3) by using the mean of the three samples per subarea. With more extensive sampling at the outcrop and subarea scales, it is altogether possible that significant surfaces can be generated for the remaining elements and that more complex surfaces can be justified.

Evaluation of the geological significance of the surfaces shown in figure 3 must be tentative because of the limited area covered. However it may be noted that the surfaces strike approximately parallel to the southern contact of the pluton and to the strike of schlieren within the body. The surfaces for Mg and K account respectively for 76 percent and 59 percent

* With 90 percent confidence, the improvement in fit more than offets the reduction in degrees of freedom corresponding to the increased number of coefficients.

Table 2A. Mean compositions and standard deviations of specimens obtained by different methods.

Specimen	Na		Mg		Al		Si		K		Ca		Ti		Fe	
	$\bar{x}$	s	$\bar{x}$	s	$\bar{x}$	s	$\bar{x}$	s	$\bar{x}$	s	$\bar{x}$	s	$\bar{x}$	s	$\bar{x}$	s
Cores																
3-inch	2.36	.11	2.00	.33	8.94	.29	27.47	1.04	1.12	.29	4.83	.53	.47	.06	5.07	.71
6-inch	2.36	.11	1.97	.31	8.97	.29	27.72	1.11	1.11	.28	4.80	.54	.47	.05	5.01	.64
12-inch	2.36	.11	2.00	.30	8.97	.29	27.66	1.08	1.11	.29	4.82	.55	.47	.05	5.12	.64
Hand specimens																
Distance from core																
5 feet	2.36	.12	1.94	.25	9.06	.35	27.72	.98	1.11	.31	4.78	.57	.47	.04	5.06	.53
300 feet	2.30	.18	2.02	.41	8.96	.58	27.65	.80	1.15	.37	4.74	.58	.49	.07	5.25	.98

Table 2B. Comparisons of standard deviations for 3- and 6-inch cores.

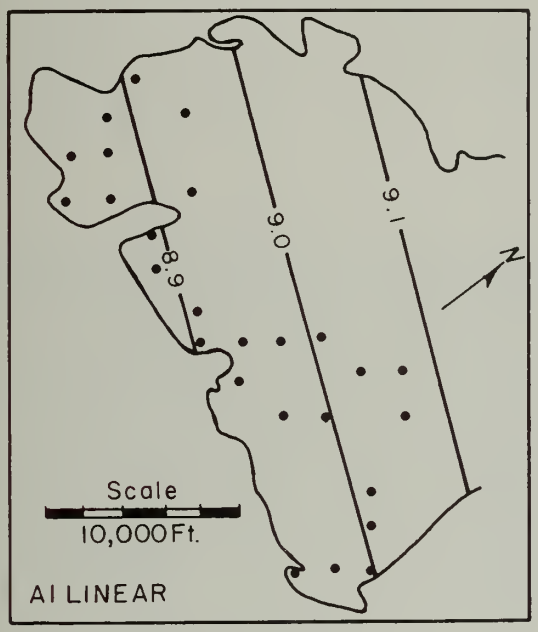
Core size	Na	Mg	Al	Si	K	Ca	Ti	Fe
Between 3-inch segments within 6-inch cores	.05	.22	.26	.43	.23	.28	.04	.31
Between 6-inch segments within 12-inch cores	.06	.21	.26	.40	.21	.24	.02	.41

f the total variability of these elements. These facts uggest that it will be possible to map the abundances f some of the major elements in the pluton as a vhole.

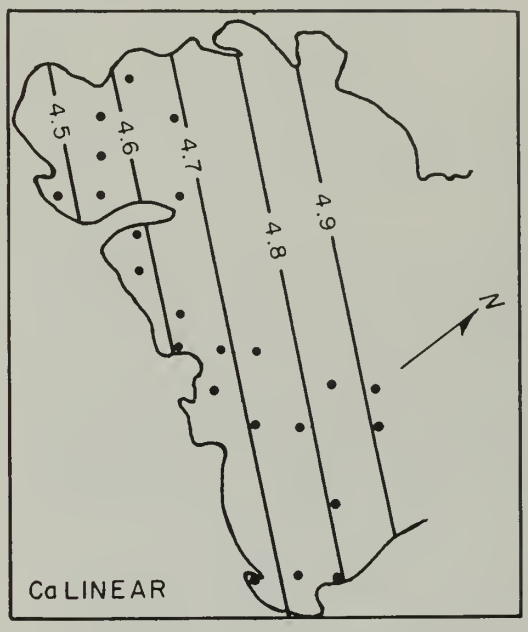
COMPARISON WITH OTHER ROCK BODIES

On the scales of outcrop and subarea (as defined in his paper) the Lakeview Mountain Tonalite was ampled in the same way as the plutonic bodies at Cactus Flat and Rattlesnake Mountain referred to above. The hornblende quartz monzonite of the Rattlesnake Mountain area is similar to the tonalite of the Lakeview Mountains in that both locally show schlieren. In the hornblende quartz monzonite the schlieren are less obvious in single outcrops but they are clearly defined when viewed from some distance.

At Cactus Flat no schlieren were found and mineralogical heterogeneity takes a different form: though a "type locality," both muscovite quartz monzonite and biotite quartz monzonite are present and both

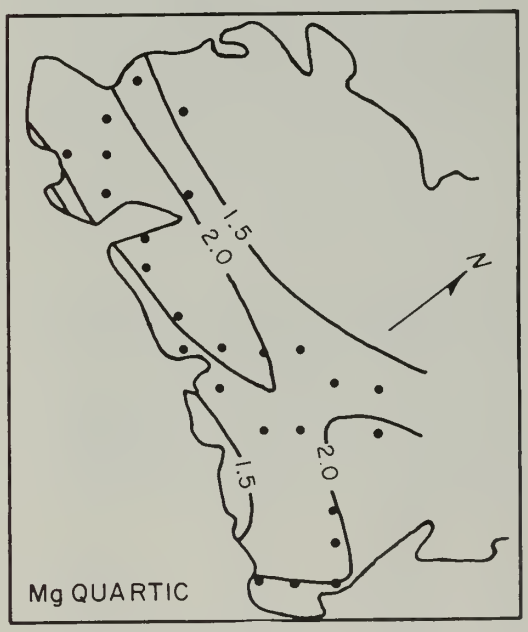


Cantaur interval 0.1% Al.
Trend surface accaunts far 16% TSS.



Cantaur interval 0.1% Ca.
Trend surface accaunts far 24% TSS.

Cantaur interval 0.1% K.
Trend surface accounts far 59% TSS.



Contaur interval 0.5% Mg.
Trend surface accaunts far 76% TSS.

Figure 3. Elemental trend surfaces for aluminum, calcium, potassium and magnesium in the southern part of the Lakeview Mountains. Dots are sample localities; TSS = total sums of squares. See text for discussion.

Table 3. Comparisons of sample variabilities in three plutonic rock units.

Rock	Scale (within)	Components of standard deviation by sampling scale (s in wt%)							
		Na	Mg	Al	Si	K	Ca	Ti	Fe
Lakeview Mountains Tonalite	Outcrop	.17	.24	.34	.32	.20	.23	.030	.47
	Subarea	N.S.	.24	.35	N.S.	N.S.	N.S.	.052	64
Rattlesnake Mountain area Hornblende quartz monzonite	Outcrop	.08	.09	.32	.80	17	23	.030	47
	Subarea	.13	N.S.	N.S.	N.S.	27	N.S.	N.S.	N S.
Cactus Flat Biotite quartz monzonite	Outcrop	.04	.03	<.15	.27	08	.15	.010	09
	Subarea	N.S.	N.S.	N S.	N.S.	18	.23	N.S.	11

N.S. Component not significant at 95% confidence.

were sampled. In this paper we include comparisons with the mapped biotite-bearing type only. However, the heterogeneity of the biotite quartz monzonite is locally increased by transitions to the muscovite-bearing type (see Richmond, 1965, for details).

In Table 3 comparisons of the chemical variabilities by scale are shown for outcrops and subareas in these three plutonic bodies. Each shows relatively high components of elemental variability within individual outcrops, however, the variabilities are least in the Cactus Flat rocks and these lack schlieren.

THE DESIGN OF FUTURE SAMPLING PLANS

Important restrictions are placed on the minimum number of localities that must be sampled over the whole area if trend surfaces of high complexity are to be used for the study of regional chemical patterns. This is because the number of coefficients used in the polynomial expressions becomes larger as the surface becomes more complex, and hence the number of degrees of freedom decreases. The number of localities must exceed the number of coefficients and we believe a factor of at least two is necessary; probably a minimum of 100 localities is needed in the Lakeview Mountains. A uniform distribution would result in a sampling grid interval similar to that shown in figure 2; however, because of lack of exposure not all grid points will be available for sampling.

Table 4. Effective local variability at grid points expected as a result of proposed sampling plan for the Lakeview Mountain Tonalite in the Lakeview Mountains. Figures are standard deviations in weight percent of the element.

Element	Total subarea variability		Component of variability over 10 sq. mi.
	This test	Expected	This test
Na	.19	.07	N.S.
Mg	.34	.12	.38
Al	.49	.17	N.S.
Si	.34	.15	.85
K	.21	.07	.29
Ca	.25	.08	.53
Ti	.06	.02	N.S.
Fe	.69	.23	N.S.

Once the total number of localities is established, evaluation of Table 3 permits us to design sampling plans in which a balance is achieved between the number of chemical analyses to be performed, the number of specimens per locality to be collected, and the time and effort available. If 100 localities are included, a large part of the sampling effort will be expended in travel. Because the components of standard deviations at the 5-foot interval account for a large part of the total variability, it is necessary to collect enough specimens to estimate adequately the mean composition of each locality. This will be only slightly more difficult than collecting a single specimen.

On the basis of the pilot study described here, the following sampling methods are proposed for the Lakeview Mountain Tonalite in the Lakeview Mountains: 140 to 160 samples are to be collected at points on the extension of the existing 2000-foot grid (see figure 2). As close as possible to each grid intersection, nine specimens of from 300 to 500 grams are to be collected by sledge hammer at 50-foot intervals on a smaller grid. The 50-foot interval is suggested as a compromise between the 5-foot and 300-foot intervals used in the preliminary test. After the specimens have been crushed, 100-gram splits from each will be combined to form one composite sample per locality. This sample will be split to form two duplicate analytical preparations.

Estimates of the standard deviations associated with the grid points of this proposed sampling plan can be obtained from

$$s^2 = \frac{s_a^2}{2} + \frac{s_r^2 + s_o^2}{9}$$

where these symbols have the same significance as before, and s^2 is effective variance for a given element at the grid locality. The results given in Table 4 show

that a three-fold reduction in the subarea standard deviation can be expected. This will provide more sensitive tests for regional variations of the elements over the pluton. In the tonalite body which margins the east side of the pluton (see figure 2), it is proposed to obtain samples in the same manner, except that the grid interval will be halved so that sufficient localities will be included for elemental trend analyses.

The total number of samples will be 180 to 200 and the number of elemental determinations will be nearly 3000. We expect to obtain the following information from these analyses:

1) The mean elemental compositians and standard deviatians far the whale expased part af the Lakeview Mauntain plutan;
2) The mean elemental campas tions and standard deviations far the adjacent tanal'te bady;
3) Contaur maps of the chemical variability.

CONCLUSIONS

The results of this preliminary test of chemical variability and field sampling methods in the southern part of the Lakeview Mountain Tonalite show that regional chemical studies over the whole body are feasible and are likely to yield meaningful results. The tonalite has a relatively high chemical variability on the scale of the outcrops and to overcome this we propose to collect nine specimens, 50 feet apart, at each grid point. We have shown that the required volume for each specimen can be as small as 3 inches by $\frac{7}{8}$-inch of core. By combining the nine specimens from each grid point to form one composite sample, the number of chemical analyses can be reduced to the minimum necessary to check analytical precisions and gross errors.

The evidence suggests that grain size is the controlling factor in determining minimum required *specimen* size and that internal layering of the rock is the controlling factor in determining the minimum required *sample* size.

APPENDIX

Terminology

When a population of interest is too extensive to be studied in all its parts, we must base our conclusions on a sample defined in such a way that it is an unbiased representative of the whole.

Given the sample values $x_1, x_2, \ldots, x_i, \ldots, x_n$ we have:

summation $$\sum_{i=1}^{n} x_i = x_1 + x_2 + \ldots + x_i + \ldots + x_n$$

mean $$\bar{x} = \frac{1}{n} \sum_{i=1}^{n} x_i$$

variance $$s^2 = \frac{1}{n-1} \sum_{i=1}^{n} (x_i - \bar{x})^2$$

standard deviation $$s = \sqrt{s^2}$$

These statistics, derived from a sample, are of interest because they estimate the unknown parameters of the population. If the sample is unbiased, the reliability of these estimates is measured by the number of degrees of freedom. In this case the number is $n - 1$ because the variance is computed from the sum of the squares of n deviations from the mean $\bar{x}$, of which only $n - 1$ are independent.

If two measurements are made on each of n rocks the results can be set down in an array of n rows and 2 columns. Analysis of variance provides an algebraic procedure whereby the total variance in the array can be portioned into one component that measures the variance between the rows (rocks) and another that is a pooled estimate of the variance between—measurements nested within—rocks. The degrees of freedom from these components are $n - 1$ and n respectively.

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THE EFFECTS OF PROVENANCE AND BASIN-EDGE TOPOGRAPHY ON SEDIMENTATION IN THE BASAL CASTAIC FORMATION (UPPER MIOCENE, MARINE), LOS ANGELES COUNTY, CALIFORNIA*

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ABSTRACT

The bosol sedimentory rocks of the Castaic Formotion illustrate the relationship between sedimentation at the morgin of a transgressing seo ond the noture af the lond being tronsgressed. The sediments, ranging from poorly sorted cobble-boulder conglomerate to well sorted sandstone, were derived fram locol source areos: the coorser grained, more poorly sorted sediments from source areas of relatively coorse-grained and erosion-resistant strato; the finer grained and better sorted sediments from source oreos af relatively finer groined and less erosion-resistont stroto. Furthermore, structural deformation ond resultont topogrophic relief were greater in the former source areos thon in the lotter. The mast important foctars controlling neor-shore sedimentation were the topographic relief of the adjacent land and the texture af the sediment thot cauld be derived from it.

On the basis of the contained fossils, it is deduced: (1) The sediments along the steep rocky part of the shore, consisting moinly of wedge- and lens-shaped bodies of sand and pebble gravel, were deposited in very shallow water. (2) These sediments, in lorge part, were rewarked and redeposited in deeper woter as tangues af sand and gravel extending from the basal cantoct out inta the offshare area of mud and sond depasition. Thus, most af the basal sediments in the Ridge basin were reworked before final deposition. Most of the sediments that were deposited neor share are poarly preserved, because they were removed and redeposited as offshore tangues of sand and grovel. These affshore tangues, preserved and now expased, camprise the bulk of the bosal stroto of the Costaic Formation.

The Castaic Formation consists of upper Miocene clastic sedimentary rocks in the Soledad and Ridge basins, east of the San Gabriel fault, in Los Angeles County, California (figs. 1, 2). In the Ridge basin, north of the town of Castaic, the formation is approximately 7000 feet thick; in the Soledad basin, southeast of Castaic, the formation is much thinner because of subsequent erosion and probably less deposition. In the Ridge basin, the Castaic Formation unconformably overlies the marine Paleocene and Eocene strata commonly referred to as the "Martinez Formation." In the Soledad basin, the Castaic Formation overlies with slight angular unconformity the nonmarine, upper Miocene Mint Canyon Formation. In the transitional area between the two basins, the formation is in fault contact with the Vasquez Formation except near Elizabeth Lake Canyon, where it unconformably overlies the Vasquez Formation. The San Gabriel fault was active during the deposition of at least the upper half of the Castaic Formation. The relationship of the Castaic Formation to adjacent correlative sedimentary rocks west of the fault depends upon the amount of lateral movement that has taken place along the fault since the late Miocene. Crowell (1954), Jahns and Muehlberger (1954), Muehlberger (1958), and Paschall and Off (1961) provide additional details of the regional geology.

The sediments of the Castaic Formation and its lateral equivalents were deposited along the margin of a transgressing sea, both along an open coast and within an embayment (fig. 3). These sediments can be divided into three lateral facies (fig. 4): (1) the lower part of the Violin Breccia as mapped by Crowell

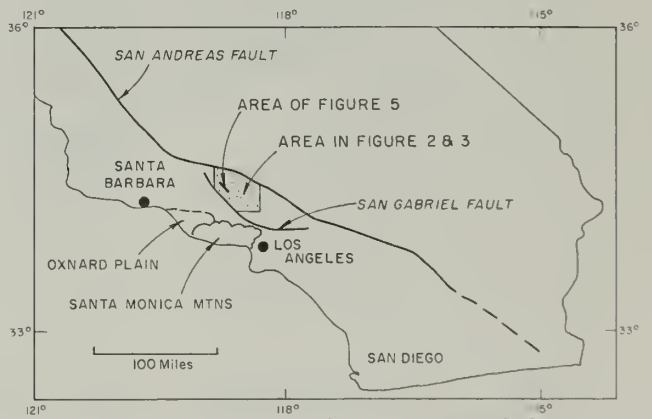
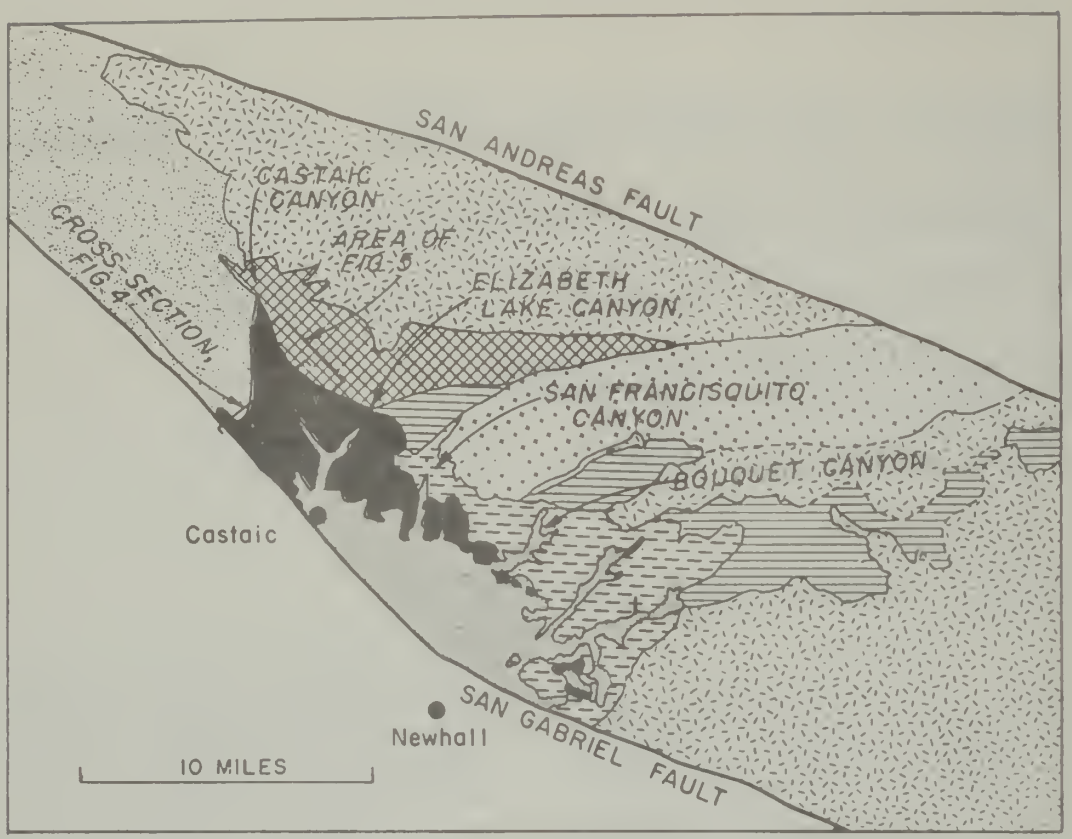


Figure 1. Map showing locotion of orea studied.

* Revised and extracted from: Paleoecology of the Upper Miocene Castaic Formation, Los Angeles County, California by R. J. Stanton, Jr., California Institute of Technology Ph.D. dissertation, 1960. Contribution No. 1328, Division of Geological Sciences, California Institute of Technology.



QUATERNARY TO PLIOCENE		ALLUVIUM, SAUGUS FORMATION, TOWSLEY FORMATION.
PLIOCENE		RIDGE BASIN GROUP
UPPER MIOCENE		CASTAIC FORMATION
UPPER TO LOWER MIOCENE		MINT CANYON AND TICK CANYON FORMATIONS
OLIGOCENE (?)		VASQUEZ FORMATION
EOCENE-PALEOCENE		MARTINEZ FORMATION
CRETACEOUS TO PRECAMBRIAN ?		PLUTONIC AND GNEISSIC ROCKS, INCLUDING ANORTHOSITE IN S.E.
PRECAMBRIAN		PELONA SCHIST

Figure 2. Geologic map of Castaic Formation and adjacent rock units (modified after Bailey and Jahns, 1954).

1954), composed of poorly sorted sediments deposited adjacent to the active San Gabriel fault in the Ridge basin; (2) a complex of sand and gravel beds deposited as basal sediments along the eastern margin of the area; and (3) interbedded mud and sand deposited offshore from the other two facies. Interfingering contacts separate the facies laterally. This paper is concerned with the second facies mentioned—the basal transgressive facies.

BASAL FACIES

The basal facies can be divided into two principal rock types which were deposited along separate parts of the shore. The transitional boundary between the Soledad and Ridge basins of sedimentation lay between the present-day locations of San Francisquito and Elizabeth Lake Canyons. In the Ridge basin, the basal strata are lenticular and are highly variable in texture, ranging from sandstone to boulder conglomerate. In the Soledad basin, the basal strata are laterally continuous beds, principally of sandstone.

Ridge Basin

The basal strata consist of a complex of lenticular and areally restricted sandstone and conglomerate beds that laps against the basal contact, extends as tongues from the contact half a mile or more out into the mudstone facies, and is divisible in detail into numerous lens- and wedge-shaped beds. The overlapping and laterally discontinuous nature of the basal strata is illustrated in figure 4 and photo 1. Lateral variability is best illustrated in figure 5; the detailed lenticularity of the strata is best illustrated in Map 1, in which unit 1, mapped as a single bed in figure 5, can be subdivided east of Cordova Ranch into nine distinct lenticular beds on the basis of differences in texture, color, fossil content, and degree of cementation.

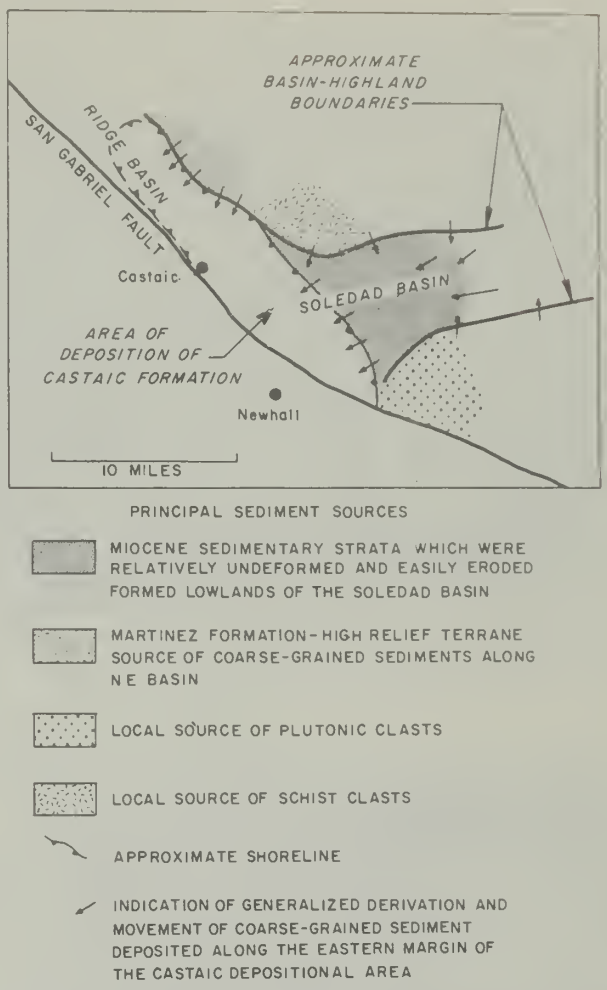

APPROXIMATE BASIN-HIGHLAND BOUNDARIES
RIDGE BASIN
SAN GABRIEL FAULT
Castaic
SOLEDAD BASIN
AREA OF DEPOSITION OF CASTAIC FORMATION
Newhall
10 MILES
PRINCIPAL SEDIMENT SOURCES
MIOCENE SEDIMENTARY STRATA WHICH WERE RELATIVELY UNDEFORMED AND EASILY ERODED FORMED LOWLANDS OF THE SOLEDAD BASIN
MARTINEZ FORMATION-HIGH RELIEF TERRANE SOURCE OF COARSE-GRAINED SEDIMENTS ALONG N E BASIN
LOCAL SOURCE OF PLUTONIC CLASTS
LOCAL SOURCE OF SCHIST CLASTS
APPROXIMATE SHORELINE
INDICATION OF GENERALIZED DERIVATION AND MOVEMENT OF COARSE-GRAINED SEDIMENT DEPOSITED ALONG THE EASTERN MARGIN OF THE CASTAIC DEPOSITIONAL AREA

Figure 3. Depositional setting of the Castaic Formation showing approximate shoreline during deposition of that part of the formation described herein, topographic boundaries, and principal source areas.

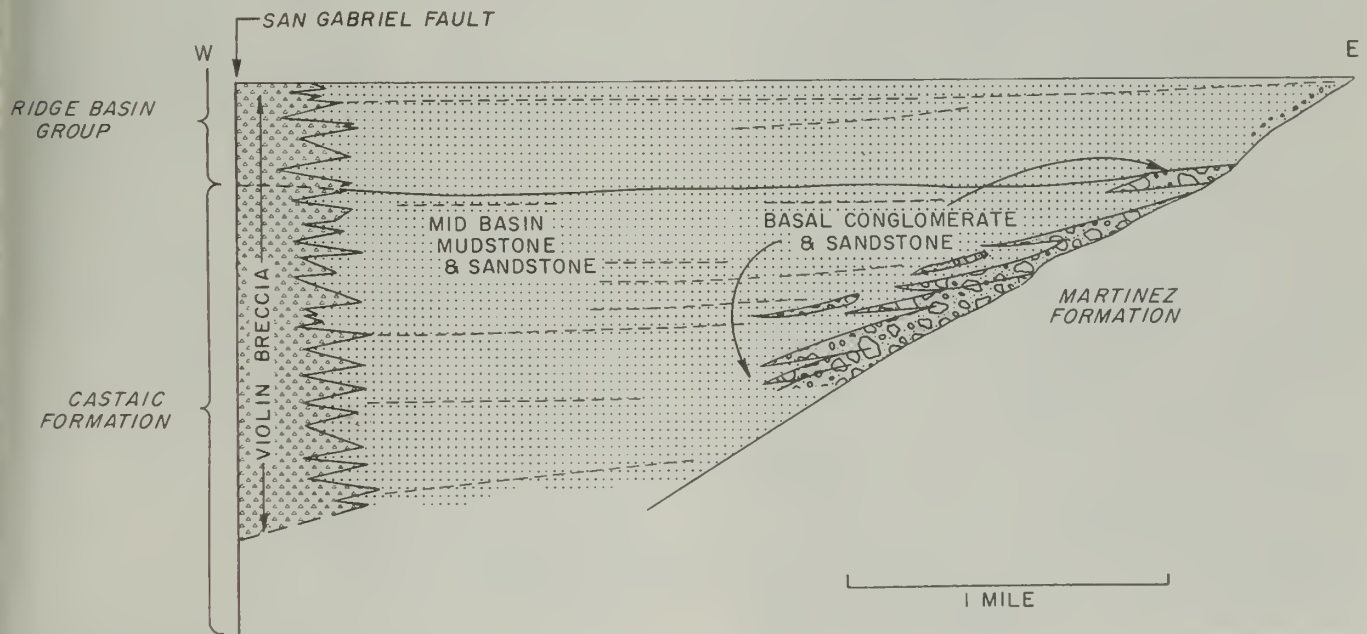


Figure 4. Diagrammatic cross section in northern part of outcrop area (Castaic Canyon area) indicating relationship of facies within the Castaic Formation. Deformation and erosion subsequent to deposition not portrayed.

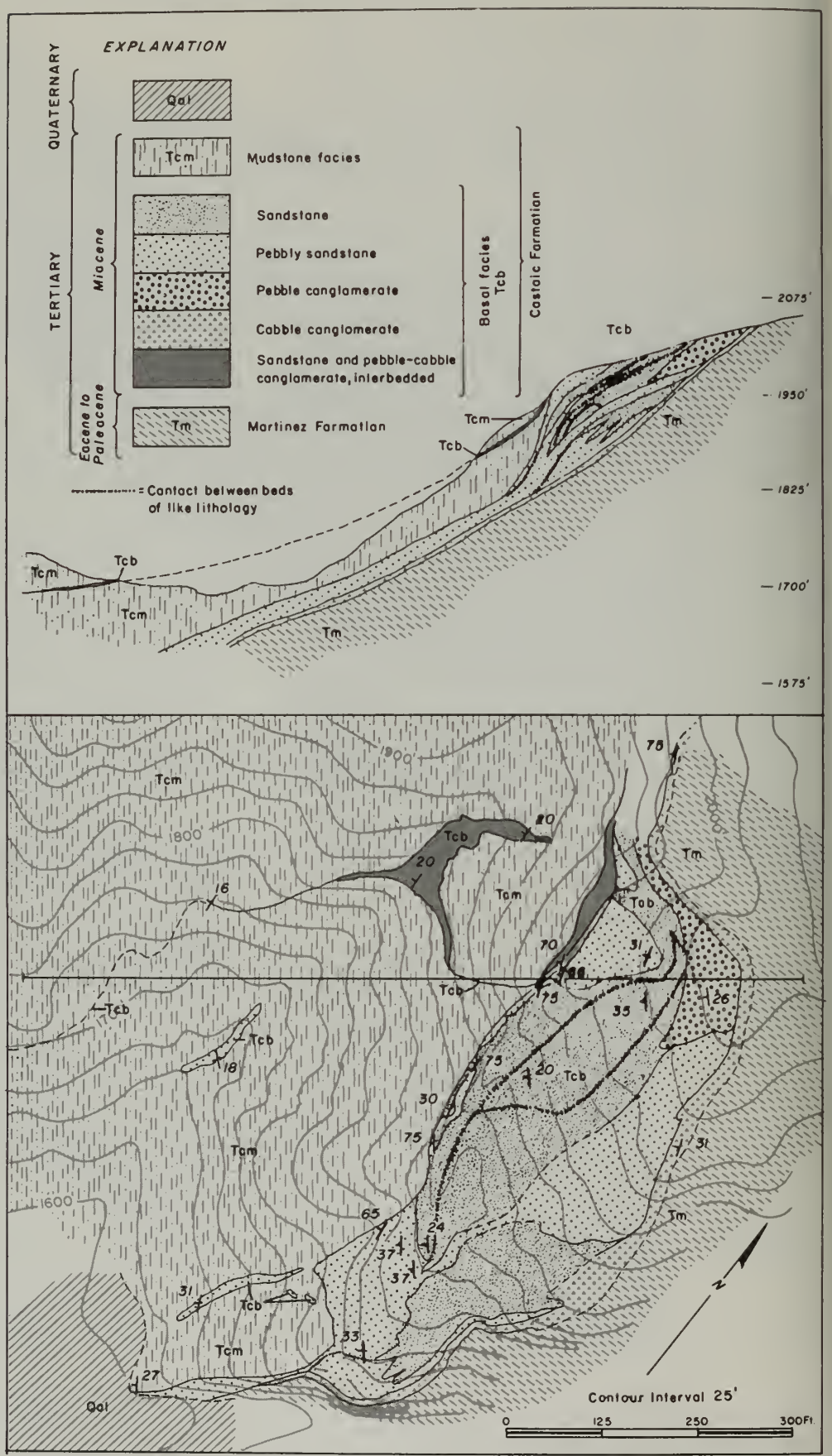


Figure 5. Geologic map and diagrammatic cross section of a portion of the Castaic Formation.

Phota 1. Basal strata an narthwest side af Castaic Canyan. *A.* Reddish conglomerate; *B.* Cobble-boulder conglomerate; *C.* Pebbly sandstone, grading ta canglamerate at right; *D.* Cabble canglamerate with sandstone lenses; *E.* Sandstone with interbeds af pebble conglomerate; *F.* Sandstone with interbeds af pebble canglomerate; pebble cantent decreases upward. Marine fossils have been found in units C, E, and F. Note onlapping to right.

The basal strata in the Ridge basin range from sandstone to boulder conglomerate but pebbly sandstone is the most common rock type. The clasts were derived from strata of sandstone and of pebble-cobble conglomerate in the "Martinez Formation". The clasts in the "Martinez" conglomerate strata are well rounded, spherical, and composed of quartzite, gneiss, and volcanic and plutonic igneous rock types. Redeposited in the Castaic Formation, they comprise about three-fourths of all clasts less than 6 inches in diameter, and nearly all the pebble-size clasts. They were apparently redeposited with little additional abrasion or rounding, for the corners and edges of those broken during redeposition are angular with little evidence of wear. All the clasts greater than 6 inches in diameter and the remaining one-fourth of those smaller than 6 inches are composed of "Martinez" sandstone and are well rounded to angular.

The basal strata in the Ridge basin generally contain abundant marine fossils, are light gray in color, and are well cemented with calcite. A subsidiary rock type is a poorly consolidated, uncemented, unfossiliferous reddish conglomerate (Photo 2). Clasts of "Martinez" sandstone in this rock type are angular to subrounded rather than rounded to well rounded as in the predominant lithology of the basal facies. Sorting is poor; a complete gradation from earthy matrix to blocks as much as 6 feet across is present. The reddish conglomerate was deposited in isolated patches along the basal contact within the Ridge basin. Its distribution in the northern half of its outcrop area is indicated in figure 4. The factors controlling the distribution are unknown; however, several occurrences appear to be confined to areas that were topographically low along the basin edge. The reddish color, lack of marine fossils, and resemblance in texture and sedimentary structure to alluvial fan deposits sug-

Phota 2. Outcrop af reddish conglomerate northeast af Cordava Ranch.

gest that the reddish conglomerate was deposited onshore along the margin of the Castaic sea as localized fans and valley fill.

The reddish conglomerate in Elizabeth Lake Canyon and between San Francisquito and Elizabeth Lake Canyons has been mapped previously as the Mint Canyon Formation (see Clements, 1937); Jahns and Muehlberger, 1954; and Crowell, 1954). The conglomerates in this area closely resemble those in Castaic Canyon and differ in lithology, texture, and sedimentary structure from the Mint Canyon strata of the Soledad basin, and are not, in outcrop, continuous with the Mint Canyon Formation of the Soledad basin. Although the red conglomerate is probably nonmarine, like the Mint Canyon Formation, it is much more closely associated in age and depositional setting to the rest of the Castaic Formation.

The basal strata in the Ridge basin were deposited on a surface of considerable relief. Allowing for subsequent tilting toward the west, the seaward dip of the basal unconformity surface was greater than 15 degrees along much of the eastern margin. In addition, the presence of local relief on the surface is indicated by small hills of "Martinez Formation" rising through the basal strata and by basal strata butting against small cliffs.

Soledad Basin

The strata of the basal facies in the Soledad basin, in contrast to those in the Ridge basin, are laterally continuous beds of sandstone to cobble conglomerate. Conglomerate is a minor component of the facies and, as exposed, was deposited on the basal contact in discontinuous patches; sandstone is the principal rock type. The strata overlie the basal contact with little evidence of onlapping against the surface. Local relief on the contact does not exceed 10 feet per 100 feet and relief on a larger scale probably did not exist.

The pebbles and cobbles in the basal strata in the Soledad basin are rounded to well rounded. Clasts of "Martinez" lithologies are rare south of San Francisquito Canyon. Volcanic and granitic lithologies are predominant; anorthosite, metamorphic rock types and tuffaceous sedimentary rocks are less abundant.

PROVENANCE

Differences in texture, bedding, and composition of the basal facies in the Ridge basin and Soledad basin can be related to the differences in provenance and depositional setting which are described below.

Depositional Setting

The Soledad basin originated during the late Eocene and early Oligocene epochs. Faulting and folding following the deposition of the Vasquez Formation was the last strong deformation within the Soledad basin and subsequently the Vasquez Formation was actively eroded during deposition of the nonmarine, lower to upper Miocene Tick Canyon and Mint Canyon Formations. Subsequent deformation within the Soledad basin prior to deposition of the Castaic Formation was, by comparison, much less, so that although the Castaic Formation overlies the Mint Canyon Formation unconformably, the two formations are discordant only locally. Thus, by the time the Castaic Formation was being deposited in the Soledad basin, a broad surface of low relief had been formed there on the strongly deformed but long-eroded Vasquez Formation and the slightly deformed Tick Canyon and Mint Canyon Formations.

In contrast, the Ridge basin, formed by the dip-slip component of movement along the San Gabriel fault, probably did not exist prior to the late Miocene as a significant localized site of deposition. Little, if any, sediments older than the Castaic Formation had been deposited in it, so that the outcropping basal sediments of the Castaic Formation were deposited directly upon the "Martinez Formation", and to a lesser extent on the Vasquez Formation in the transitional area between the two basins. The strongly deformed and relatively erosion-resistant strata of the "Martinez Formation" provided a depositional surface for the Castaic Formation that was of relatively much higher relief than that present in the Soledad basin.

Clast Sources

In the Ridge basin, the "Martinez Formation", forming the terrane being transgressed, contained numerous beds of cobble conglomerate and of well-indurated sandstone. Thus, it was a potential source of sandstone clasts up to boulder size and of well rounded cobbles of igneous and metamorphic rock types derived from the conglomerates. In the Soledad basin, sources of clasts were the highland area of Pelona Schist to the northeast, the plutonic and gneissic rocks in the San Gabriel mountains on the southeast, and the older Tertiary strata within the basin. The strata within the basin were a source for sedimentary and volcanic clasts as well as metamorphic and plutonic clasts reworked from the adjacent basement terranes. Compared to the "Martinez Formation", however, the sedimentary rocks within the Soledad basin were able to furnish a lesser amount of clasts for they were less well indurated and contained fewer conglomerates.

PROVENANCE—SEDIMENTATION RELATIONSHIPS

Texture

The texture of the basal sediments of the Castaic Formation was determined by the local availability of coarse grained clastics. The sediments were derived from local source areas with negligible longshore transport of sediment coarser than sand. The supply of clasts in the Martinez Formation in conjunction with relatively high relief in the source area and the nearness of the source area to the sea resulted in conglomeratic basal strata. Clasts derived from the "Martinez Formation" are almost entirely restricted to Castaic strata directly overlying the "Martinez Formation". In the Soledad basin as well, clasts were derived from local sources. Clasts are primarily igneous and metamorphic lithologies and were derived in large part, and perhaps entirely by reworking sediments from the Mint Canyon, Tick Canyon, and Vasquez Formations. The importance of local sources is illustrated by the composition of the clasts at different out-

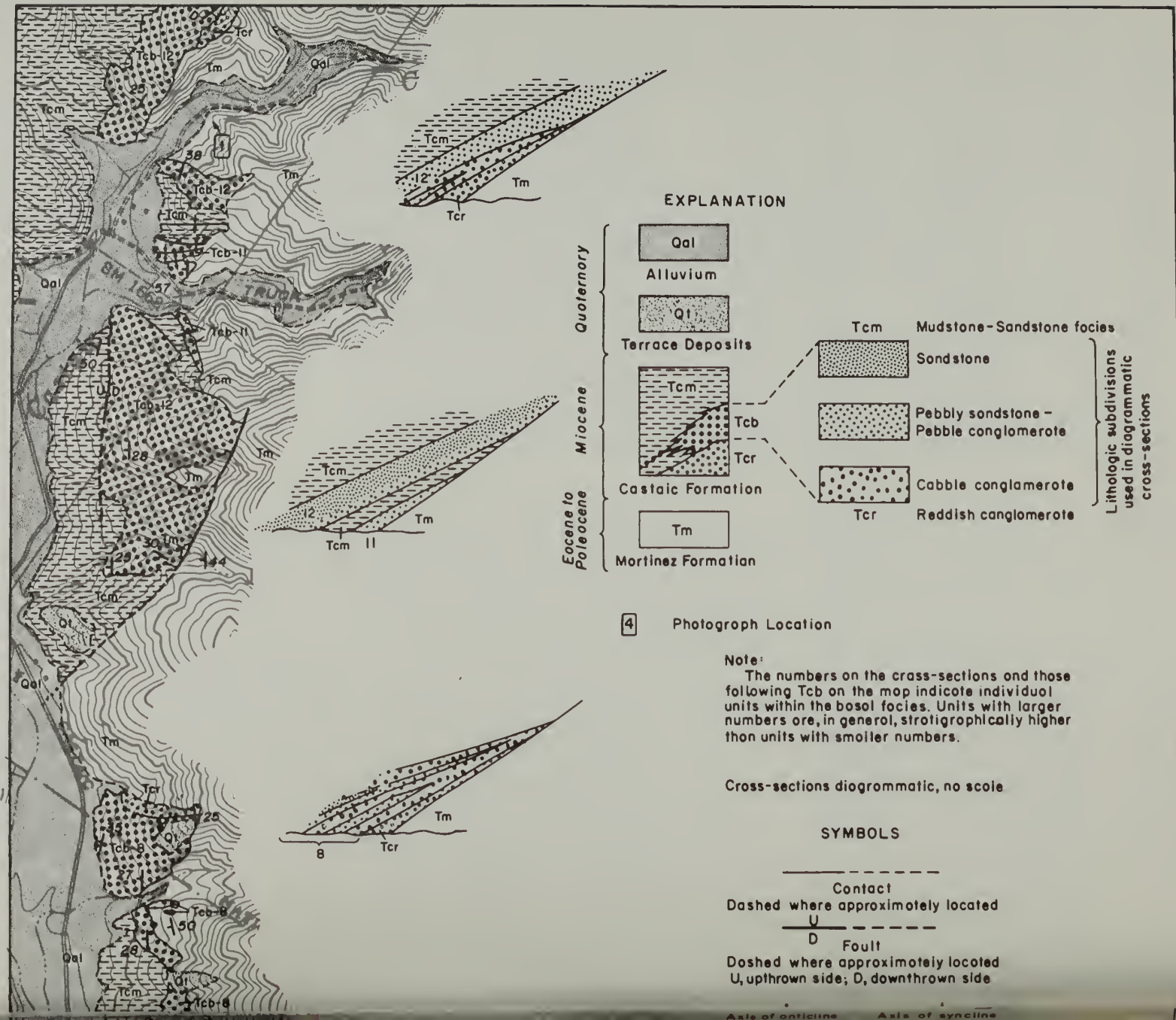
Table 1. Fossils from basal sandstone and conglomerate strata.

	A "Nearshore"	B "Offshore"	Habitat (most common bathymetric distribution in brackets)	Relationship
Pelecypods				
Nuculana (Sacella) ochsneri (Anderson and Martin)	R		[3–10]—51 fm [sand] and mud	*N. taphria*
Glycymeris cf. *G. gigantea* (Reeve)	C		<7 fm sand	Species
Glycymeris grewingki Dall	C			
Lyropecten estrellanus (Conrad)	C			
Lyropecten crassicardo (Conrad)	A			
Spondylus sp.	C		[low tide] to 20 fm—attached to rocky substrate	Genus
Crassostrea titan (Conrad)	A		[low tide to a few fm]	Genus
Ostrea vespertina Conrad	R		[low tide to a few fm]	Genus
Pseudochama sp.	R		[intertidal]—60 fm—attached to hard substrate	Genus
Newcardium (Keenaea) centifilosum (Carpenter)		C	10—[30–40]—108 fm—sand	Species
Dosinia sp.	R		4–35 fm—sand and mud	*D. ponderosa*
Chione (Securella) elsmerensis English	C			
Psammotreta Florimetis biangulata (Carpenter)	R		intertidal—[0–few fm]—25 fm—sand	Species
Sanguinolaria cf. *S. nuttallii* Conrad	R		low tide—2½ fm—sand	Species
Corbula (Lentidium) lutecla Carpenter	R		[intertidal and shallow water among rocks] to 25 fm	Species
Boring pelecypods	A			
Gastropods				
Patellid gastropods	R		[intertidal to a few fm] on rocks or kelp	Patellaceae
Tegula gallina (Forbes)	R		intertidal, rocky substrate	Species
Astraea sp.	R		[low tide—few fm]	Genus
Nerita sp.	R		intertidal—rocky substrate	Genus
Turritella cooperi Carpenter		A	10—[30–50]—80 fm—sand and gravel	Species
Vermetidae	R		intertidal to few fm—hard substrate	Family
? *Bittium arnoldi* Bartsch		R		
Polinices uber (Valenciennes)	R		intertidal—50 fm	Species
Neverita reclusiana (Deshayes)	C		[intertidal—few fm]—25 fm—sand	Species
Sinum scopulosum (Conrad)		R	few fm—40 fm—sand	Species
Ficus (Trophosycon) ocoyana (Conrad)		R		
Ocenebra cf. *O. topangensis* Arnold	R			
Forreria carisaensis (Anderson)	R			
Pyrene sp.		R	intertidal, under and between rocks	Genus
Kelletia vladimiri Kanakoff	R			
Cancellaria cf. *C. fernandoensis* Arnold	R			
Cancellaria tritonidea Gabb	R			
Olivella (Olivella) pedroana (Conrad)	R		[intertidal]—50 fm—sand	Species
Conus californicus Hinds	C		[intertidal—10]—80 fm—sand, gravel, among rocks	Species
Conus sp.	R			
Bulla sp.		R	low tide to 20 fm—sand and mud	Genus
Echinoderms				
Astrodapsis fernandoensis Pack	A			
Cidarid spines	R			
Bryozoans—encrusting	R			
Barnacles—*Balanus*	C		[intertidal to a few fm]—hard substrate	Genus
Clionid ? borings	A			

Key: R Rare C Common A Abundant fm Fathoms.

crops (fig. 3). The clasts of volcanic composition were definitely derived from the underlying Oligocene and Miocene formations and are widely distributed in the basal strata. Clasts derived from the Pelona Schist are largely confined to basal strata exposed north of Bouquet Canyon, near the outcrops of Pelona Schist. The conglomerates which crop out south of Soledad Canyon are largely of gneissic and plutonic igneous rock reflecting the dominant lithologies of the nearby western San Gabriel Mountains.

Conglomerates in the Castaic Formation are less abundant overlying the Vasquez and Mint Canyon Formations than above the "Martinez Formation" for three reasons: 1) the local sediment sources, the Mint Canyon, Tick Canyon, and Vasquez Formations were much less indurated than the Martinez Formation and thus tended to weather and to erode to sand and mud; 2) conglomerates are less numerous in these formations than in the "Martinez Formation", so the supply of ready-made clasts was less; 3) because of the lower relief of the land surface formed on these formations, few clasts derived from the igneous and metamorphic terranes to the east and southeast were transported to the site of deposition of the Castaic Formation. Only in the southern part of the outcrop area, near the San Gabriel Mountains, was perhaps a significant amount of clasts supplied directly from the igneous source.


EXPLANATION
Quaternary
Miocene
Eocene to Paleocene
Qal
Alluvium
Qt
Terrace Deposits
Tcm
Tcb
Tcr
Castaic Formation
Tm
Mortinez Formation
Tcm Mudstone-Sandstone facies
Sandstone
Pebbly sandstone - Pebble conglomerate
Cobble conglomerate
Tcr Reddish conglomerate
Lithologic subdivisions used in diagrammatic cross-sections
4 Photograph Location
Note:
The numbers on the cross-sections and those following Tcb on the map indicate individual units within the basal facies. Units with larger numbers are, in general, stratigraphically higher than units with smaller numbers.
Cross-sections diagrammatic, no scale
SYMBOLS
Contact
Dashed where approximately located
U
D
Fault
Dashed where approximately located
U, upthrown side; D, downthrown side
Axis of anticline
Axis of syncline

Map 1. Detailed stratigraphy east af Cardava Ranch, shawing lenticularity of basal strata of Castaic Farmatian (Unit Tcb). See figure 5 far lacation.

Sedimentary Structure

Differences in the bedding characteristics of the basal facies—in the degree of lenticularity, of variability of lithology from bed to bed, and of overlapping on the unconformity—are related primarily to the differences in the tectonic and erosional history within the region. These differences in geologic history determined the general topographic setting in which the Castaic Formation was deposited. The greater relief in the Ridge basin than in the Soledad basin was also, in part, the consequence of the more erosion resistant strata being transgressed within the Ridge basin.

The contrasting onshore topography, sediment sources, and basal depositional surfaces in the Ridge basin and in the Soledad basin were probably similar to the contrasts found today along the southern California coastlines of the Santa Monica Mountains on the one hand and the adjacent Oxnard plain at the mouth of the Santa Clara River valley on the other hand.

DEPOSITIONAL PROCESS—BASAL FACIES IN THE RIDGE BASIN

By analyzing the contained fossils, much can be determined about the manner of deposition of the basal facies that could not be determined from the inorganic constituents alone. In this analysis, the organisms now preserved as fossils were either buried in place where they lived, or were transported elsewhere before burial. By comparing the fossils with Recent conspecific or closely related taxa, the water depths where the organisms were living and finally buried can be estimated. If the transported shell is considered as a clast, some details of sediment movement can thus be determined.

Organisms buried in place, where they lived, can be recognized in general by such characteristics as good skeletal preservation, the articulation of bivalves, preservation in growth position, and, based on comparison with Recent conspecific or closely related taxa, occurrence in a sedimentary matrix that would have formed a suitable substrate and the occurrence together of species that might have lived together. Transported shells, by comparison, should be generally less well preserved and not in growth position; bivalves should be disarticulated, and the fossils should occur with sediment and with other fossils with which they would not have occurred in life.

The fauna of the Castaic Formation in the Ridge basin consists primarily of mollusks, with brachiopods, echinoderms, barnacles, and bryozoans as minor components. In Table 1, the abundance of the taxa within the basal facies are indicated and depth and substrate distribution data are given, based on the known distributions of Recent analogous taxa along the west North American coast. The relationships of the Recent taxa are noted: some species are still living; for an extinct species, data are given for a closely related species or for the genus or larger taxon including that species. No data are given if this Recent larger taxon has a broad, nondiagnostic ecologic range, or if no closely related or analogous taxon exists at present. The Recent data are based on a comprehensive search of the literature. The most valuable references are Burch (1944–46), Hertlein and Strong (1940–51), and Keen (1958). Useful recent compilations of molluscan ecologic data have been made by Valentine (1961) and by Winterer and Durham (1962). The most common bathymetric distribution is bracketed in the table, if known.

Sandstone and pebbly sandstone beds lying near the basal contact in the Ridge basin contain abundant shells which are commonly in growth position, unworn and, if pelecypods, articulated (photo 3). This fauna is listed in column A of Table 1. It is composed of species that either lived on a sand substrate or on the rocky substrate, intertidally and in shallow water. Some of the species are restricted to the intertidal habitat; the rest range from the intertidal or base of the intertidal out into water not deeper than a few tens of fathoms. As a whole, the fauna in column A is suggestive of water not more than about 5 fathoms deep. Thus, the strata containing these fossils in place were deposited along shore in very shallow water. Conglomerate beds lying near the basal contact and sandstone to conglomerate beds in the tongues extending basinward from the basal contact also contain the

Photo 3. Articulated and single valves of *Lyropecten crassicardo* in basal pebbly sandstone, east of Cordova Ranch. Scale is 6 inches long.

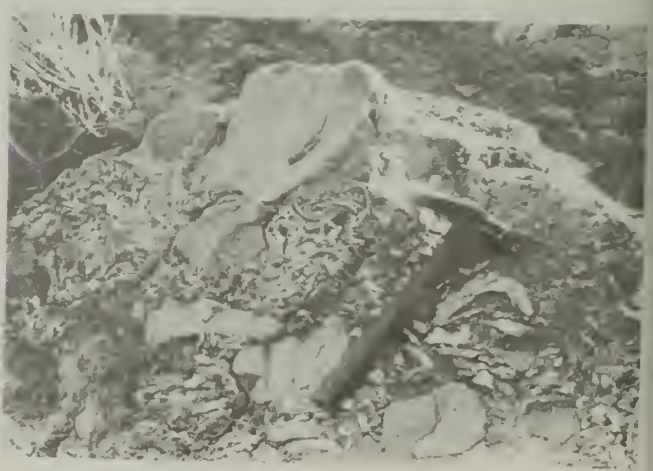


Photo 4. "Offshore" tongue of conglomerate composed of shell fragments and clasts of "Martinez" sandstone, northwest of Cordova Ranch.

same assemblage. However, the shells are generally broken, disarticulated, and occur in a matrix much coarser grained and less well sorted than the substrate in which they would have lived (photo 4). Thus the specimens in the conglomeratic strata were transported from their near shore habitat before burial.

Species that are restricted to the offshore tongues, away from the basal contact, and have not been found associated with in-place assemblages of the shallow water fauna described above are listed in column B. *Turritella cooperi* and *Nemocardium centifilosum* are the only abundant elements of the fauna; the other species are represented by only a single specimen or a few specimens each in the collections made. The two abundant species are still living and are most commonly found at depths of 30 to 50 fathoms. The rare species are most common in shallower water and must probably have been transported before burial; because of their rarity, they were not found in the shallow water sediments. The faunas in columns A and B are denoted as "nearshore" and "offshore" on the basis of relative bathymetry, and secondarily, on relative lateral nearness to the basal contact. The "offshore" specimens (column B) are generally unbroken and unabraded in contrast to the "nearshore" specimens with which they are associated in the tongues of basal strata. In addition, at localities where species from both assemblages occur together, the largely broken and disarticulated "nearshore" specimens are by themselves within beds; the better preserved "offshore" specimens are commonly in adjacent strata or along bedding planes betwen strata containing the "nearshore" species.

The ecologic significance of the two faunas, their distribution, and their state of preservation in different settings lead to the interpretation that the tongues of basal sedimentary rock consist of sediment and shells reworked from shallow water nearshore into adjacent deeper water where the substrate was populated by a different molluscan fauna. Thus the reconstructed depositional environment would be one in which, during most of the time, mud was being deposited in mid-basin and to within a few hundred feet of the steep rocky shore. Along the basin edge, the rocky shore and the substrate of sand and pebbly sand in water a few fathoms deep supported a distinctive fauna. The abundance of *Crassostrea* specimens as much as 18 inches long and *Lyropecten* specimens as much as 8 inches across indicate that these conditions were not greatly disturbed for long periods of time. At infrequent intervals, no doubt associated with heavy storms, the nearshore substrate and organisms were in large part eroded, mixed with pebbles and cobbles from along shore or newly introduced into the marine environment, and then redeposited along shore and as tongues extending basinward for distances up to a mile and into water 30 to 50 fathoms deeper. Subsequently, a distinctive deeper-water assemblage would inhabit the sandy substrate afforded by the tongues until they were buried by mud.

CONCLUSIONS

The texture, structure, and composition of the basal sediment in the Castaic Formation reflect the lithology and tectonic history of the land surface being covered by the transgressing sea. By analyzing the megafaunal assemblages present in the basal strata deposited along the shore of relatively high relief, it is concluded that much of the basal sediment was deposited in shallow water along shore and provided a habitat for abundant organisms. At infrequent intervals, however, these sediments and organisms were reworked and redeposited in deeper water away from shore. Final deposition was at distances as great as one mile from shore. Thus much of the basal sedimentary rocks now preserved represent not the usual but the occasional depositional environment. Because the different assemblages of fossils are indicative of particular environments, fossils which have been transported before final burial may indicate details about the manner of sedimentation that the inorganic clasts can not provide.

ACKNOWLEDGMENTS

The author is indebted to H. A. Lowenstam for his helpful guidance during this study. Financial support was furnished by the National Science Foundation, the Marathon Oil Company, and the California Institute of Technology. N. L. McIver and H. A. Lowenstam have reviewed the manuscript and offered many helpful suggestions.

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SEDIMENTARY ROCKS OF LATE PRECAMBRIAN AND CAMBRIAN AGE IN THE SOUTHERN SALT SPRING HILLS, SOUTHEASTERN DEATH VALLEY, CALIFORNIA

By BENNIE W. TROXEL *

ABSTRACT

The southern Solt Spring Hills is the southern port af a small range that extends south across the sautheost-trending Death Valley traugh in eastern California. The hills lie within 1 mile of the southwest limit of the Basin Ronges province, which is defined by the Gorlock fault zone at the narth base af the Avawatz Mountains, ond lie also a few ta a few score miles within the sauthwestern limits af the Cardilleran geosyncline of lote Precambrion and Cambrian time.

The sedimentary rocks include a partiol section, abaut 3,600 feet thick, of the Kingston Peak Formation of late Precambrion age; the Johnnie Formotian and Stirling Quartzite af late Precambrian age; and the Wood Canyon Formation ond Zobriskie Quartzite af Cambrian age. Port af the Kingston Peak strata appeor to be glacial-marine in origin. The past-Kingston Peak strata are marine sedimentary stroto that total 3,400 feet in thickness as compared ta a thickness af 7,500 feet far the same rock units in the Nopah Range, 25 miles ta the nartheast.

Other rocks include small masses af Mesazoic(?) hornblende-biatite quartz manzonite intrusive into the sedimentary rocks; Quaternary fan deposits; and a small playo that was formed ot the north end of the hills in late(?) Pleistocene time as a result af temparary panding af woter fram the Mojave River.

Several normol faults cut the rocks in the sauthern Salt Spring Hills, presumably in Tertiory time, after the strata were falded inta a shollow nartheast-trending syncline.

The southern Salt Spring Hills is a range of hills 7 miles long and 2 miles wide that trends north along the middle of the eastern edge of the Avawatz Pass 15-minute quadrangle in the southeasternmost part of Death Valley. California Highway 127 bisects the hills: the part lying north of the highway is herein referred to as the "northern Salt Spring Hills", and the southern part as the "southern Salt Spring Hills".

As a continuation of geologic mapping by the writer, started in southern Death Valley in 1953, the southern Salt Spring Hills were mapped in 1955 in 4 days on a portion of the Avawatz Pass 15-minute quadrangle, at a scale of 1:24,000.

Sections in the Johnnie Formation, Stirling Quartzite, Wood Canyon Formation, and Zabriskie Quartzite were measured and described by Wright and Troxel (1956) and a section in the Kingston Peak Formation was measured by the writer in 1964. The Kingston Peak Formation was measured on south-facing slopes in the south end of the southern Salt Spring Hills. The Johnnie Formation was measured on a south-facing slope of the southern Salt Spring Hills, 2500 feet southwest of section line "A-B" on the geologic map and about 400 feet west of a northeast-trending fault shown on the map. The Stirling Quartzite, Wood Canyon Formation, and Zabriskie Quartzite sections were measured on an east-trending line extended approximately across the north edge of the highest peak in the northern Salt Spring Hills. The formations are not significantly different in thickness or lithology in the southern Salt Spring Hills.

ROCK UNITS

Regional Setting

In southern Death Valley, the lowermost exposed rocks are strongly metamorphosed rocks that are overlain by relatively unmetamorphosed sedimentary rocks of the Pahrump Group of late* Precambrian age. Rocks of the Pahrump Group, which is comprised of the Crystal Spring Formation, Beck Spring Dolomite and the Kingston Peak Formation are widespread throughout southern Death Valley and in general are very similar in lithology to type sections in the Kingston Range described by Hewett (1940, 1956) some 25 miles northeast of the southern Salt Spring Hills.

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* The terms "early" and "late" Precambrian are used informally herein: "late" Precambrian is used to designate the age of the Pahrump Group, Noonday Dolomite, Johnnie Formation, and Stirling Quartzite; "early" Precambrian refers to the age of all crystalline rocks that lie beneath the Pahrump Group in the southern Death Valley area. The terms "lower" and "upper" are used informally also for time-stratigraphic units equivalent to those designated as late or early Precambrian in age.

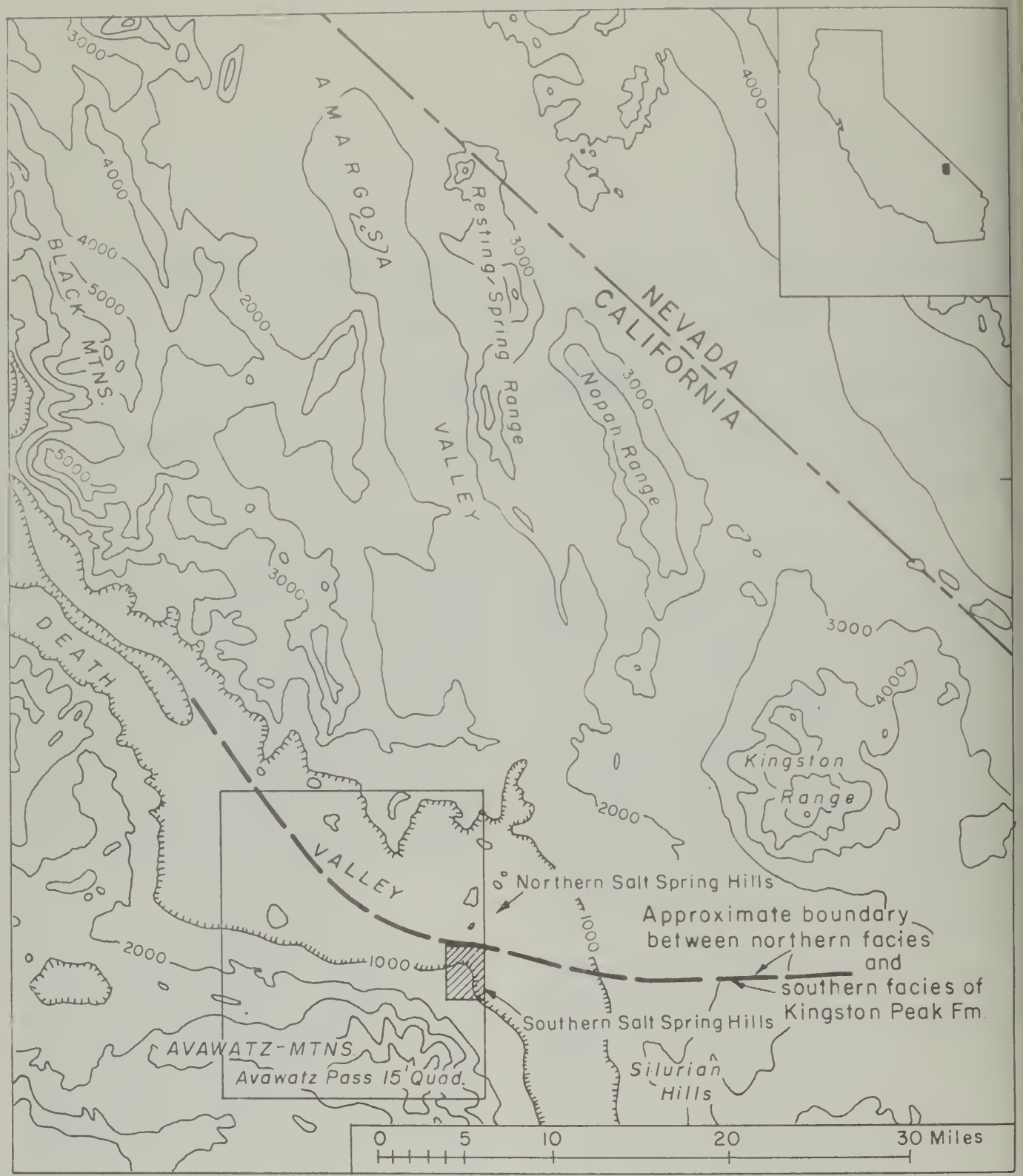


Figure 1. Index map showing location of southern Salt Spring Hills, Californio.

A widespread unconformity separates the Kingston Peak Formation from the overlying upper Precambrian Noonday Dolomite which is successively overlain by upper Precambrian Johnnie Formation and Stirling Quartzite, and the Cambrian Wood Canyon Formation and Zabriskie Quartzite. Significant stratigraphic changes occur within the Kingston Peak Formation below the unconformity and the Noonday Dolomite above the unconformity.

The Kingston Peak Formation appears to comprise at least two facies separated along a northwest-trending line that extends through southern Death Valley (index map, figure 1). The northern facies consists of three principal units—a lower shale, a middle conglomerate, and an upper quartzite—and is characterized throughout by a deep maroon to pale green color. It extends in a belt 10 to 20 miles wide from the east side of the Kingston Range to the west side of the Black Mountains. The southern facies occupies a belt at least 5 miles wide that underlies the floor of southern Death Valley and widens to the northwest and southeast. This facies generally is very dark gray in color and consists of conglomerate and quartzite.

Each of the two facies of the Kingston Peak Formation is characterized by a different assemblage of rock types in the conglomerate clasts. Clasts in the northern facies consist of a high proportion of Beck Spring Dolomite and subordinate amounts of Crystal Spring and lower Precambrian rocks, and all derived from source areas situated north of the present exposures. Clasts in the southern facies consist solely of strongly metamorphosed lower Precambrian rocks, and probably derived from sources to the south. The southern Salt Spring Hills contain excellent exposures of the Kingston Peak Formation and the most complete section of the southern facies exposed between the Silurian Hills and the Panamint Range, west of Death Valley.

The Noonday Dolomite, which is widespread in the southern Death Valley region and which typically consists of dolomite, gives way southwestward to a siliceous clastic section along a northwest-trending line that extends approximately along the northeast margin of southern Death Valley. Neither the dolomite nor the siliceous sediments of the Noonday Dolomite crop out in the Salt Spring Hills. The lowermost strata above the Kingston Peak Formation that crop out in the southern Salt Spring Hills comprise a thin unit of hornfels not identified elsewhere in the Death Valley region and are included herein in the Johnnie Formation. The remainder of the Johnnie Formation as well as the Stirling Quartzite, Wood Canyon Formation, and Zabriskie Quartzite contain the lithologic characteristics that allow them to be so readily identified in the southern Basin and Range province but they are generally coarser grained and all but the Zabriskie Quartzite are greatly reduced in thickness.

Upper Precambrian Rocks

Kingston Peak Formation

The Kingston Peak Formation crops out in the southern quarter of the southern Salt Spring Hills. It dips northeast and is broken into several blocks by faults. Many of the details of bedding are masked by deep-brown desert varnish or by rubble on the outcrops. Sedimentary structures can be observed in stream banks along the south margin of the hills.

In the southern Salt Spring Hills the Kingston Peak Formation is divided into five informal units which aggregate about 3,600 feet in thickness. The identification of the lowest unit (unit a) is not clearly determined. It is composed of pinkish to pale brownish-gray fine- to coarse-grained quartzite characterized by cross-beds and prominent even bedding, and is about 400 feet thick. It underlies the small west tip of the southwestern knob of the southern Salt Spring Hills and is separated from other strata by a fault. Similar but darker and more strongly cross-bedded quartzite beds about 1,100 feet thick that crop out in an isolated small patch about 2,000 feet south of the main part of the southern Salt Spring Hills are also identified as unit a. Strata in both outcrop areas resemble coarse-grained strongly cross-bedded quartzite of the lower part of the Wood Canyon Formation but are more likely to be part of the Kingston Peak Formation and, if so, must underlie units b-e. Three beds of dark brown-weathering dolomite, 6 inches to 2 feet thick, occur in the lower part of the southwesternmost outcrop of unit a.

Unit b is composed of fine- to coarse-grained, moderately even-bedded, dark gray quartzite and conglomeratic quartzite. Bedding is distinct on the dark brownish-gray outcrops and faint cross-beds are common. The unit crops out only along the southeastern part of the southwestern tip of the southern Salt Spring Hills where it is 240 feet thick.

Unit c is massive dark gray conglomeratic quartzite about 700 feet thick. This unit is analogous to what is commonly called a pebbly mudstone in which isolated pebbles are widely dispersed in an unstratified fine-grained matrix. In this quartzite unit heterogeneous pebbles, cobbles, and boulders are uniformly and sparsely disseminated in dark-gray quartzite. The clasts are sub-rounded to well-rounded and are composed predominantly of lower Precambrian gneisses and intrusive rocks which are widespread beneath the Pahrump Group in the southern Death Valley region. A small proportion of the clasts are composed of quartzite and carbonate rocks that were also derived from lower Precambrian terranes. There is no obvious pattern to the clustering or scattering of clasts nor to orientation of the clasts. The clasts make up from 10 to 20 percent of the total rock. The quartzite matrix consists of fine to coarse angular to sub-rounded grains of milky white to dark-gray quartz. Bedding within this unit is extremely rare and where observed the beds are no more than a few inches thick or a few tens of feet in lateral extent. This unit underlies the southwesternmost knob of the southern Salt Spring Hills, where it is conformable with and in sharp depositional contact with units b and d.

Unit d is about 250 feet thick and crops out along the stream bed along the southern edge of the southern Salt Spring Hills. A portion of the unit is well exposed in stream banks. The unit is dark gray and is

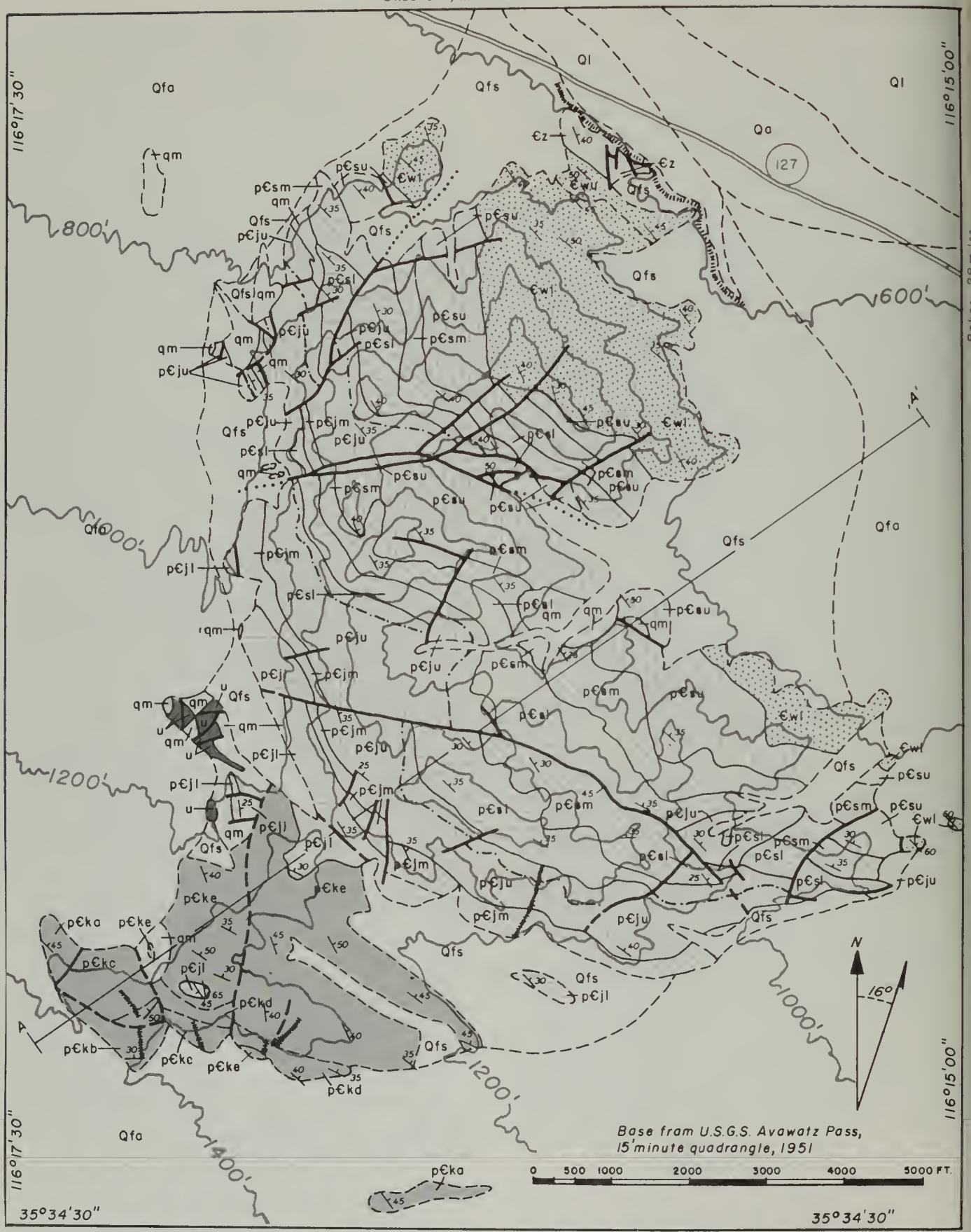
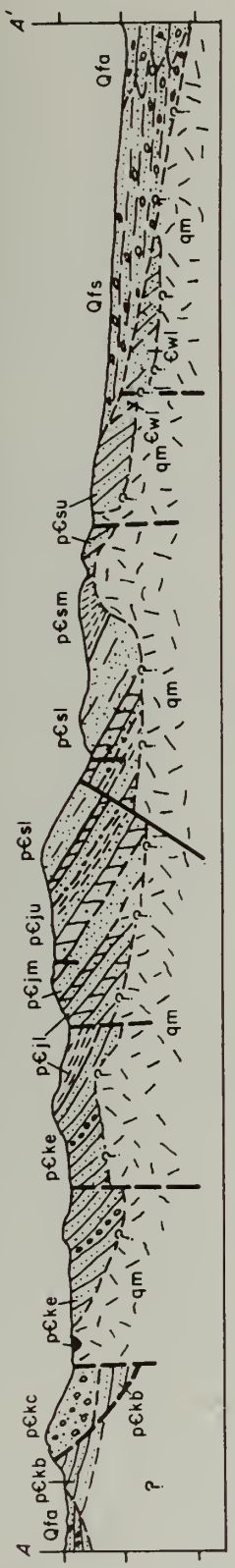


Figure 2. Geologic map of southern Salt Springs Hills, California.



EXPLANATION

Quaternary

Qa — Alluvial deposits: Qa - stream deposits

Ql — Ql - lake deposits

Qfs / Qfa — Qfs - southern Salt Spring Hills deposits; Qfa - Avawatz Mountains deposits

Mesozoic(?)

qm — Hornblende biatite quartz manzanite

Cambrian

€z — Zabriskie Quartzite

€wu / €wl — Wood Canyon Formation: €wu - upper member; €wl - lower member

Precambrian

p€su / p€sm / p€sl — Stirling Quartzite: p€su - upper member; p€sm - middle member; p€sl - lower member

p€ju / p€jm / p€jl — Jahnnie Formation: p€ju - upper member; p€jm - middle member; p€jl - lower member; — oallte bed

p€ke / p€kd / p€kc / p€kb / p€ka — Kingstan Peak Formation: units a through e

Precambrian and Cambrian(?)

u — Undivided rocks

SYMBOLS

Contact — Dashed where approximately located

Fault — Dashed where approximately located, dotted where concealed

45 — Strike and dip of bedding

Remnant of Quaternary shoreline

Location of measured section

Figure 3. Legend for geologic map and cross-sections through the Solt Springs Hills, California.

composed of very fine-grained to coarse grained quartzite beds that commonly are graded.

Individual beds in unit d are persistent in thickness along strike for at least several tens of feet and range in thickness from a fraction of an inch to about 3 feet. Exceptionally well preserved sedimentary features are exposed in stream banks. These features include distinctive grading, flame structures, current bedding at the top of graded beds, scour-and-fill features, load casts, flute casts, convolute lamination, slump structures, and bent clasts of fine grained material derived from underlying beds. The features are typical of those generally observed in turbidites. Some of the very fine-grained beds are composed of chlorite, suggesting a higher magnesium content than the coarser beds. Locally there are a few beds of pale gray dolomite no more than 1 foot thick. A few beds of coarse angular quartzite are similar in texture to the massive conglomeratic quartzite of the underlying unit. Unit d is conformable beneath unit e.

Unit e, the uppermost unit of the Kingston Peak Formation in the Salt Spring Hills is the thickest and most widespread of the five units. It is about 2,000 feet thick and underlies most of the southwestern part of the southern Salt Spring Hills. It consists of fine- to coarse-grained dark-gray to dark pinkish-brown quartzite and conglomeratic quartzite. The quartzite beds range in thickness from a small fraction of an inch to a few feet. They are well bedded, evenly bedded, and commonly distinctly bedded. Some beds are strongly and steeply cross-bedded and some are graded. Locally, the beds contain ripple marks that suggest current movement from approximately S. 15° E. Layered conglomeratic quartzite beds composed of closely packed pebbles comprise as much as 15 percent of the unit. Conglomerate clasts in massive beds are mostly in the pebble-size range and are composed of well-rounded to sub-angular pale colored quartzite.

Rocks similar to the massive quartzite of unit e, with dispersed clasts, are commonly stated to be glacial tills but the association of this type of conglomerate with rocks containing features associated with turbidites such as unit d suggest a marine environment (see Crowell, 1957). The rocks of unit c and the graded beds in unit d may have been derived from glaciers, deposited along the margins of a marine basin, and subsequently redeposited as interstratified graded and non-graded beds by submarine turbid flows.

Johnnie Formation

The Johnnie Formation crops out in the southern Salt Spring Hills as northeast-dipping strata that appear to be conformable beneath the Stirling Quartzite and to overlie the Kingston Peak Formation with a slight angular unconformity. The Johnnie Formation is 2550 feet thick in the Nopah Range (Hazzard, 1937) and 1170 feet thick in the southern Salt Spring Hills. (Wright and Troxel, 1956). In general, the Johnnie Formation is coarser grained in the southern Salt Spring Hills than in the Nopah Range and has similar lithologic characteristics.

The formation in the southern Salt Spring Hills is divided into three members — a lower member consisting of quartzite, dolomite, and dolomitic quartzite; a middle member of quartzite; and an upper member of dolomite, quartzite, and siltstone.

The lower member is incompletely exposed. It consists of two parts separated by a fault but probably little, if any, of the section is lacking. A lower thin-bedded part overlies the Kingston Peak Formation in the southern Salt Spring Hills and is not known to occur elsewhere in the southern Death Valley region. It consists of several tens of feet of very thin-bedded calc-silicate hornfels. The hornfels was probably metamorphosed by the quartz diorite which underlies the hills and crops out about 500 feet west of the main outcrop of the hornfels beds. The weathered outcrops of hornfels are yellowish-brown to greenish-brown and show that the rock is extremely thin bedded. Fresh exposures appear massive in texture, are very fine grained, and are pale olive green.

The main part of the lower member is 360 feet thick. It consists of coarse- to medium-grained, pale brownish-gray, indistinctly and thickly bedded dolomitic quartzite. Locally the member contains crude cross-beds and wavy beds of quartz grains cemented with silica.

The middle member is composed of 240 feet of quartzite with subordinate beds of dolomite and shale. The quartzite is mainly compact, tough, sub-vitreous, medium to coarse grained, and flesh colored. Bedding is indistinct except where shale partings occur. The upper 40 feet of the middle member consists of well-bedded quartzite and dolomitic quartzite.

The upper member is 570 feet thick and consists of thin to thick beds of dolomite, sandy dolomite, quartzite, and shale. The lower 100 feet is mainly dolomite and sandy dolomite. The dolomite occurs in distinct beds, mostly less than 1 foot thick, that lie between sandy dolomite beds, and are colored pale blue-gray, yellowish-brown, pale brownish-gray, dark brown, pale brown, or greenish-gray. Some of the dolomite beds are composed of dolomite chips and fragments, and some are characterized by algal forms. The next overlying 135 feet consists mostly of gray to silvery-gray shale with interbeds of quartzite and dolomite. Next above is 150 feet of quartzite with interbeds of dolomite and shale. The quartzite is mostly fine grained, dark reddish-brown, and contains numerous shale partings. Shale beds in the upper part of this quartzite appear to be tuffaceous and are overlain by 30 feet of red-stained silvery-gray shale which also appears to be tuffaceous. A few thin interbeds of fine-grained quartzite and sandy dolomite occur in the shale. The shale is overlain by a 10-foot bed of pale brownish-yellow dolomite with a distinct oolitic texture. The oolite bed serves as a very useful stratigraphic marker throughout a large region in southern Death Valley and southwestern Nevada (Wright and Troxel, 1966). The uppermost 145 feet of the upper member of the Johnnie Formation consists of fine-grained reddish-brown quartzite that grades upwards into green quartzite and shaly quartzite, then to sandy dolomite and dolomite. The contact with the Stirling Quartzite appears to be conformable.

Stirling Quartzite

Although measured in a portion of the northern Salt Spring Hills, 3 miles north of the southern Salt Spring Hills, the Stirling Quartzite is, as nearly as can be determined, the same in total thickness and lithology in both groups of hills. The Stirling Quartzite is 847 feet thick (Wright and Troxel, 1956) as compared to 2,593 feet in the Nopah Range (Hazzard, 1937). As in the Nopah Range, the Stirling Quartzite is divided into three members — a lower member of medium- to coarse-grained pale quartzite, a middle member of fine- to medium-grained dark quartzite, and an upper member of medium- to very coarse-grained pale quartzite. The comparative thicknesses, in feet, of the three members in the northern Salt Spring Hills and the Nopah Range are as follows:

	Northern Salt Spring Hills	Nopah Range
upper	342	1,273
middle	290	170
lower	215	1,150

The most complete section of Stirling Quartzite in the southern Salt Spring Hills lies between the two high peaks about one mile from the highway. The following descriptions are of strata exposed in the southern Salt Spring Hills.

The lower member consists of massive to well-bedded, medium- to coarse-grained, well-cemented, sub-vitreous, light- to medium-gray, brown, yellow- to reddish-brown quartzite. Individual beds are from a few inches to a few feet thick and commonly are marked by shale partings. Indistinct cross-beds and ripple marks are present in some of the beds.

The middle member consists almost wholly of dark brown to dark greenish-brown platy shale and thin-bedded fine-grained quartzite. The beds are distinctly marked with current ripples, drying cracks, raindrop prints, and flattened balls of clay. One thin bed of brown shaly dolomite occurs 65 feet above the base of the member.

The upper member is similar to the lower members in gross lithology, color, and topographic expression. The lower part of the upper member is a succession of rapidly alternating thin beds of fine- to coarse-grained quartzite. Some beds are pebbly and some are cross-bedded. The middle part of the upper member is massive in general appearance but thin beds are fairly distinct and uniform in grain size (medium-grained). The upper part consists of medium- to very coarse-grained quartzite beds commonly cross-bedded, and contains beds with well-rounded pebbles of pale gray quartzite. The top of the formation consists of dark greenish-gray sandy, platy siltstone, and brownish-orange pebbly quartzite.

Cambrian Rocks

Wood Canyon Formation

As mapped in the southern Salt Spring Hills, the Wood Canyon Formation includes the lithologic equivalent of the 2,241-foot-thick section in the Nopah Range that lies between the Stirling Quartzite and the Zabriskie Quartzite Member of the Wood Canyon Formation as described by Hazzard (1937). The Wood Canyon Formation is 1,265 feet thick where measured in the northern Salt Spring Hills (Wright and Troxel, 1956), and is probably nearly the same thickness in the southern Salt Spring Hills. It is divided into a lower dark medium- to very coarse-grained quartzite member 705 feet thick and an upper dark fine-grained quartzite, shale, and dolomite member 560 feet thick. The lower member corresponds in stratigraphic sequence approximately to Hazzard's members 4A to 4D and the upper member to Hazzard's members 4E to 4G. A presumably complete but poorly exposed section occurs in the northeast part of the southern Salt Spring Hills. Outcrops of the Wood Canyon Formation are masked with an unusually dark brownish-gray patina of desert varnish.

The lower member consists mostly of distinctly bedded, strongly cross-bedded medium- to very coarse-grained dark brown-weathering quartzite that commonly has a faint to moderate purplish cast. The lowermost beds are thin-bedded maroon, gray, red, and brown quartzite and shale. A thin bed of dolomitic quartzite occurs 65 feet above the base. The upper one-fourth of the lower member contains many interbeds of greenish-brown shale. Quartzite beds commonly range in thickness from a few inches to four feet.

The upper member consists of fine- to medium-grained quartzite with a high proportion of shale beds. Dolomite and sandy dolomite beds occur in the upper half of the upper member and are dark brown, orange-brown, or dark gray on weathered surfaces. Fossil trilobite debris occurs in shale beds as low as 340 feet below the top of the formation, but identifiable material was not obtained.

Zabriskie Quartzite

The Zabriskie Quartzite forms a prominent small ridge at the northernmost tip of the southern Salt Spring Hills. Where measured in the northern Salt Spring Hills, it is 170 feet thick (Wright and Troxel, 1956) and is overlain by strata of the Carrara Formation (Lower and Middle Cambrian). In the Nopah Range the Zabriskie Quartzite is 162 feet thick (Hazzard, 1937).

The Zabriskie Quartzite is strongly cemented, compact, sub-vitreous, and pale salmon-pink. It appears to be moderately even grained and medium grained but individual grains are indistinct. Pebbles, cross-bedding, and shale partings are uncommon. Beds range in thickness from one to six feet. Vertical, sand-filled tubes a quarter to half an inch thick and a few inches to about 2 feet long are common in a 5-foot bed near the base. These tubes (scolithus) are characteristic of the Zabriskie Quartzite.

Undivided Rocks

Eight blocks of quartzite, dolomite, and quartz diorite gneiss large enough to show on the map (figure 2) are contained in the largest mass of hornblende-biotite quartz monzonite along the west side of the southern Salt Spring Hills. The blocks are rotated and in stratigraphic disorder. They appear to be in intru-

sive contact with the quartz monzonite and in fault contact with each other. Quartzite blocks and dolomite blocks are lithologically similar to strata in the nearby slopes and are relatively unmetamorphosed. Quartz diorite gneiss blocks are similar in composition and degree of metamorphism to lower Precambrian rocks that lie beneath the Kingston Peak Formation throughout southern Death Valley. Most of the blocks are at least a few tens of feet wide and two to three times as long as they are wide.

Mesozoic (?) Rocks

Hornblende-biotite quartz monzonite of probable Mesozoic age crops out as isolated knobs in the fan west of the southern Salt Spring Hills, in several discontinuous masses along the west side of the hills, and in two small masses near a canyon bottom in the center of the hills.

Because similar quartz monzonite crops out in the southwestern part of the northern Salt Spring Hills and in a small hill several miles west of there, it seems reasonable to assume that the quartz monzonite underlies several square miles of the Avawatz fan west of the Salt Spring Hills as well as the central and western part of the southern Salt Spring Hills.

The rock appears to be homogeneous in composition, is coarse grained, equigranular in texture, but locally is porphyritic. Pink feldspar grains in some parts of the rock are twice as large as white feldspar and dark hornblende grains. The approximate composition, determined visually of a single hand specimen, is quartz, 15 percent; hornblende, 5 percent; orthoclase feldspar, 40 percent; plagioclase feldspar, 35 percent; and biotite 1–2 percent. Hornblende and biotite are partly altered to chlorite. Moderately sparse granitic dikes, mostly less than 6 inches thick, intrude the quartz monzonite.

The knobs of quartz monzonite form moderately steep slopes. The weathered surface is covered with dark brown equant blocks which are coated with desert varnish. An apron of coarse arkose covers the bedrock except for ribs of more resistant material. Fresh exposures are pinkish-gray.

Two sets of joint planes cut quartz monzonite. They are deeply weathered and trend north. The more prominent set dips moderately west; the other dips eastward at right angles to it. Minor joint planes trend athwart the north-trending sets.

Intrusive contacts with the sedimentary rocks are well defined and metamorphic effects on the strata are mild. The blocks of undivided rocks embedded in quartz monzonite along the west side of the southern Salt Spring Hills and the lower Johnnie hornfels are slightly more metamorphosed than any other strata in the southern Salt Spring Hills.

Quaternary Rocks

Sediments of Quaternary age are divided into four units — alluvial fan deposits of the Avawatz Mountains, alluvial fan deposits of the southern Salt Spring Hills, playa sediments, and Recent stream sediments.

Avawatz Mountains Fan Deposits

The Avawatz Mountains fan is, at the surface, a complex mosaic of debris flows. The youngest debris flows are pale gray and largely occupy active stream channels. Some have overflowed the channels and have built up the edges and sides of them. The oldest debris flows have well-developed paved surfaces and are stained very dark brown with desert varnish. The rocks consist mostly of diorite which is the main rock in the canyon of the Avawatz Mountains southwest of the Salt Spring Hills. Marble and other rocks in the drainage system have contributed a small proportion of the debris.

Clasts in the Avawatz Mountains fan range through all sizes from coarse silt to boulders 10 or more feet in diameter. Boulders of diorite and marble as large as 6 feet in diameter rest on the fan surface near the highway about 4 miles from the Avawatz Mountains. The fan appears to have been built up from material deposited from episodic debris flows rather than by gradual accumulation in stream beds.

Southern Salt Spring Hills Fan Deposits

The small fans bordering the southern Salt Spring Hills are simple in form and composition. Their composition reflects the type of rock in the source area and commonly a fan consists of a single rock type. The size of fragments in individual fans is controlled by the initial size of fragments derived from the source area and diminishes as the distance from the source area increases. The fragments are dark and evenly coated with desert varnish, suggesting that their present form has not been disturbed for a considerable length of time and that the whole surface of the fan is of about the same age.

Lake Sediments

Fine-grained sediments in the Salt Creek drainage were deposited in a temporary basin of probable late Pleistocene age. These sediments consist of a few feet to perhaps a few tens of feet of thin-bedded, evenly bedded, pale pinkish-gray to pale greenish-gray silt. The grain sizes range from clay size to fine sand. The material barely swells, if at all, when wetted. Bedding is generally indistinct on weathered slopes but beds at the south margin of the basin appear to be very gently inclined northward.

The sediments were deposited in a local basin formed when the debris of the Avawatz Mountains fan closed the drainage channel of Salt Creek (probably then the Mojave River) and caused the waters to be temporarily ponded against the fan and the quartz monzonite of the northern Salt Spring Hills. The water was ponded long enough for a wave-cut bench to be cut along the shoreline of the lake. The wave-cut bench is best developed in the talus that flanks outcrops of the Zabriskie Quartzite. Subsequently the stream cut through the quartz monzonite to form its present channel.

Stream Sediments

The youngest sediments in the southern Salt Spring Hills area are the Recent sediments that lie in the stream channels and the thin film of fine to coarse gravels that overlies the playa sediments adjacent to Salt Creek. These gravels migrate downstream during periods of heavy runoff from torrential storms. Most of the debris probably has been deposited by intermittent streams that drain the Avawatz fan southeast of the Salt Spring Hills.

Structural Features

The southern Salt Spring Hills are too small to have recorded in them many of the tectonic events that have occurred in the southern Death Valley region even though they are near the Garlock and Death Valley fault zones, which merge in the northern foothills of the Avawatz Mountains. The strata have been compressed into a shallow northeast-trending and plunging syncline and cut by normal faults.

There is no direct evidence to determine whether or not the hills are bounded by faults. At least part of the uplift and eastward tilting of the strata may have been caused by intrusion of the quartz monzonite mass that crops out along the west side of the hills. If the blocks of undivided rocks contained in the quartz monzonite are the result of forceful injection of the quartz monzonite then it seems reasonable also to assume that part of the tilt or uplift of the hills was caused by the intrusion. If the blocks are not related to intrusion then they may be a remnant of an otherwise unrecognized tectonic event that is pre-intrusion in age.

The regional unconformity at the base of the Johnnie Formation suggests tectonic activity of undetermined magnitude following the deposition of the Kingston Peak Formation in late Precambrian time. The angular discordance in this area suggests a tilting of no more than a few degrees.

Movements along the normal faults appear to postdate the intrusion of quartz monzonite. The youngest fault is a small fault that cuts the Avawatz fan west of the undivided rocks on the west side of the Salt Spring Hills. None of the faults appears to be related in trend to the Garlock and Death Valley faults but may be tensional fractures related to movement along them.

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RECONNAISSANCE GEOLOGY OF THE HELENA QUADRANGLE, TRINITY COUNTY, CALIFORNIA

By DENNIS P. COX

ABSTRACT

Four major rock units which underlie the Helena quadrangle are: 1) The Salman Hornblende Schist af pre-Permian age, probobly metamorphased in Pennsylvanian time, 2) metasedimentary racks compased mainly of thin-bedded chert, af prabable Pennsylvonian ar Permion age, 3) diobase, gabbra, and serpentine, and 4) actinalite schist and layered amphibalite. The first three units farm belts trending narthwest across the quadrangle separated by eost-dipping reverse faults. The fourth unit is expased in a windaw in the sauthwest carner af the area. All but the faurth unit are intruded by tanalite and diarite stacks af Late Jurassic age.

Gold-bearing quartz veins in the Salman Harnblende Schist were mined in several places and gold has been extracted from terrace gravel deposits by hydraulic methads.

INTRODUCTION

The area mapped lies in the Klamath Mountains of north-central Trinity County and is named the Helena quadrangle after a small town of that name on the North Fork Trinity River (fig. 1).

The area is reached by U.S. Highway 299 from Redding or Eureka. Weaverville, the county seat of Trinity County, lies 8 miles east of the quadrangle.

The central part of the quadrangle is accessible by two improved dirt roads extending from Highway 299 to Dedrick and to Hobo Gulch campground. The northern part is within the Salmon-Trinity Wilderness Area and is reached by trails.

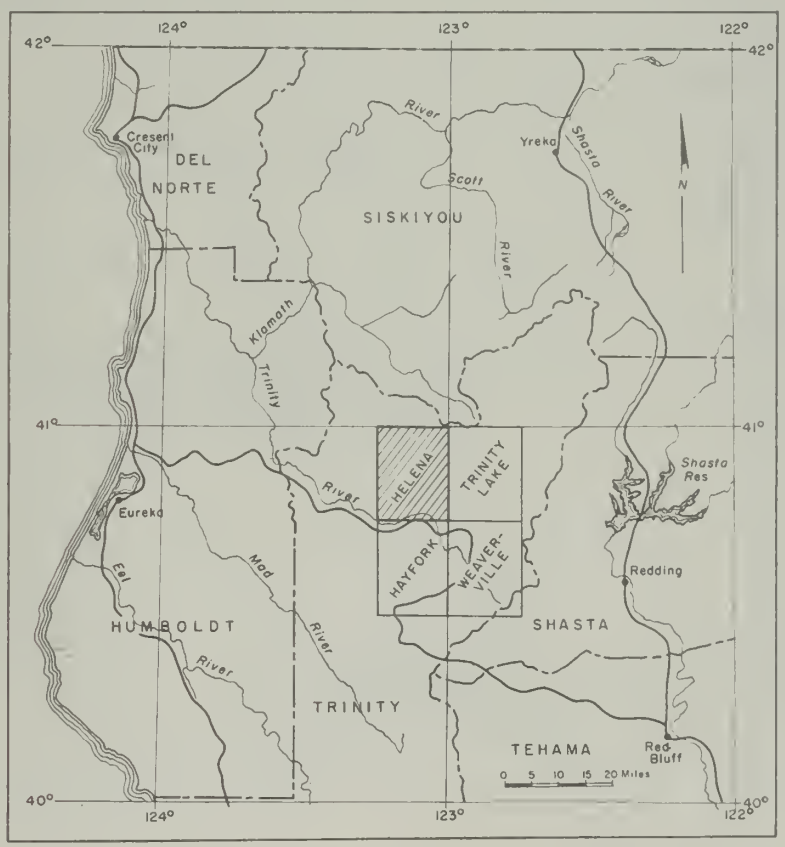


Figure 1. Index map af Califarnia shawing locatian af Helena quadrangle.

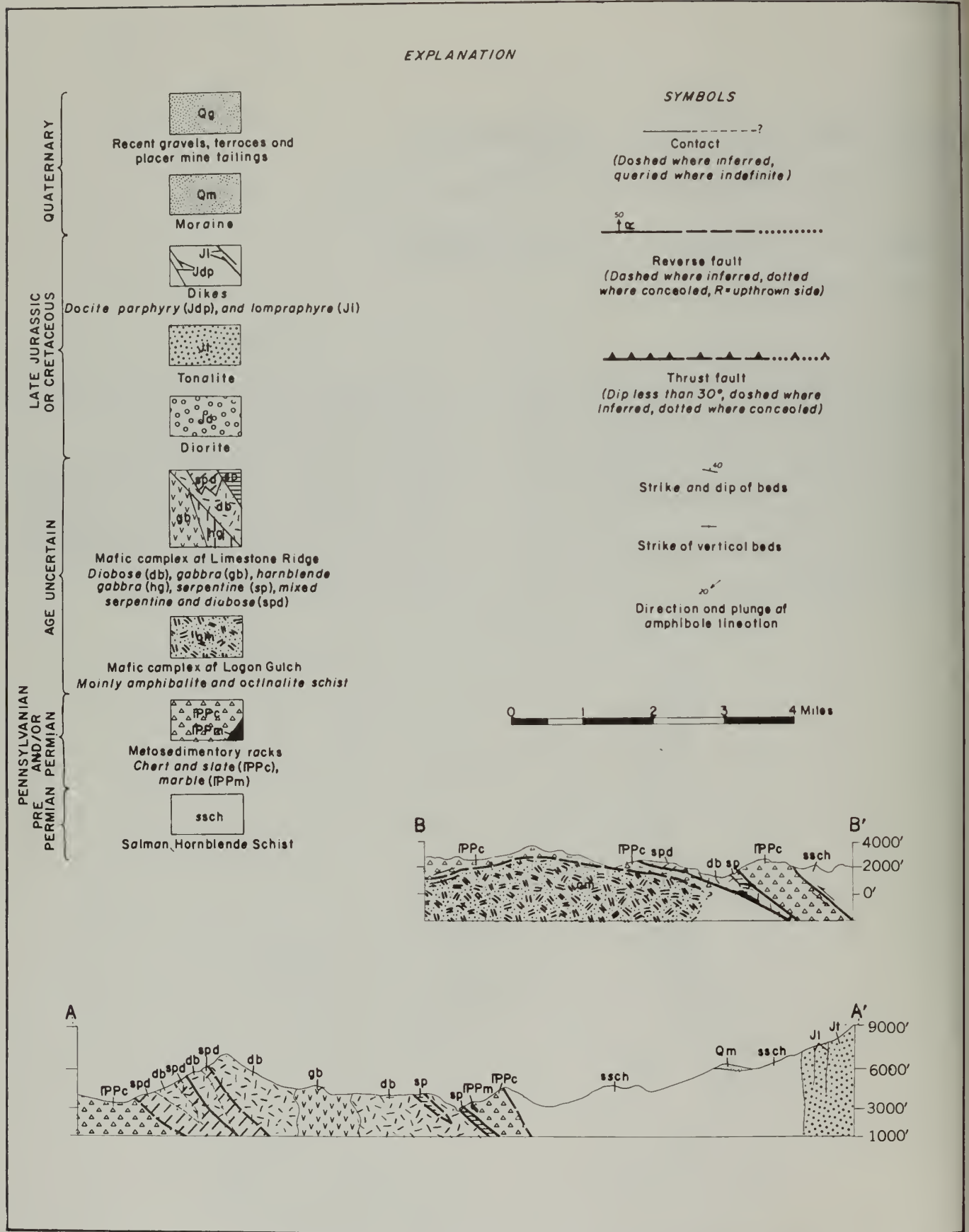
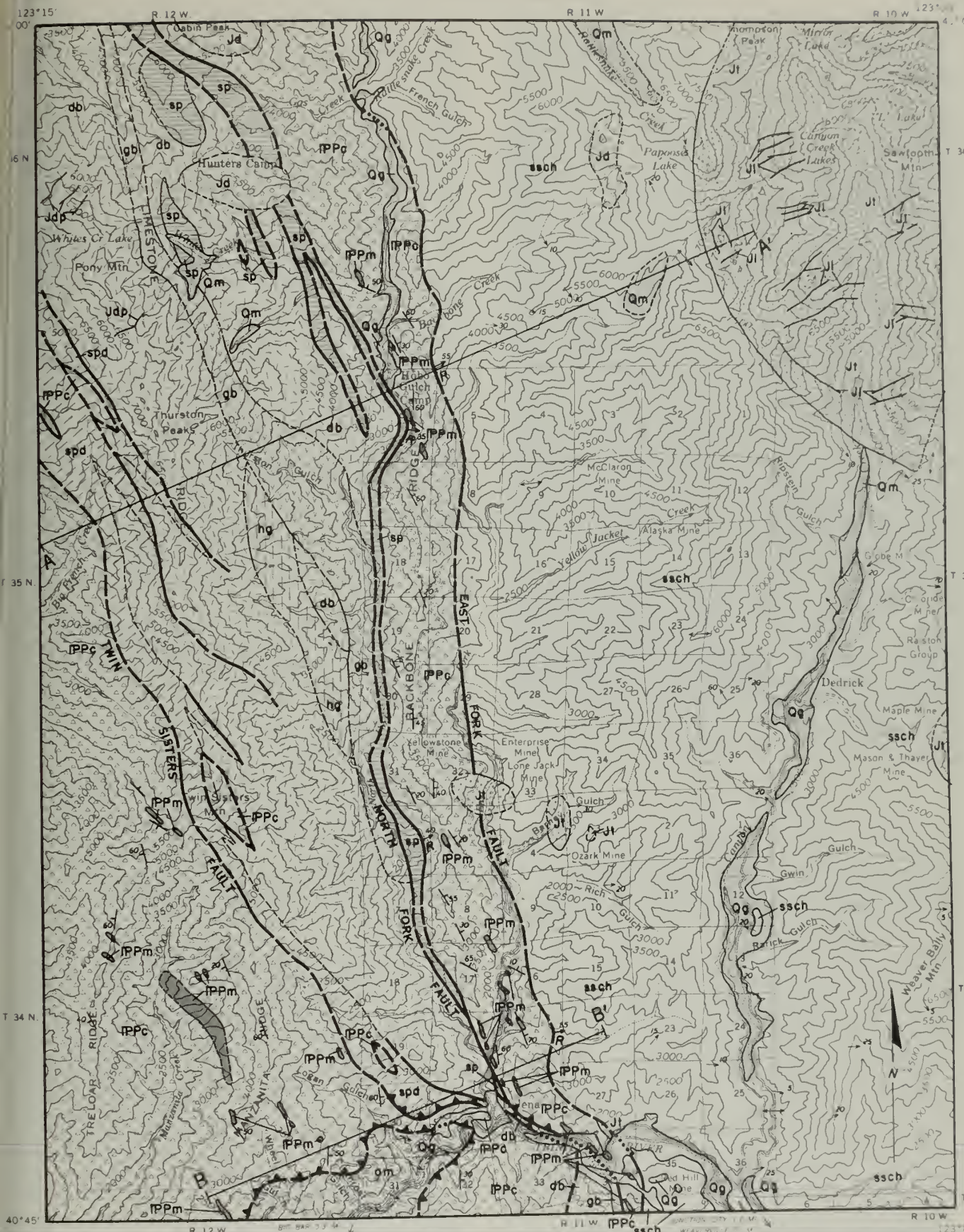


Figure 2. Reconnaissance geologic map and cross sections of the Helena quadrangle, Trinity County, California.


R 12 W.
R 11 W
R 10 W
T 36 N
T 35 N.
T 34 N.
T 33 N
Cabin Peak
Hunters Cairn
Whites Cr Lake
Pony Mtn
Thurston Peaks
Twin Sisters Mtn
Mt Hornaday
Mirror Lake
Lake
Canyon Creek Lakes
Sawtooth Mtn
Papoose Lake
McClaron Mine
Alaska Mine
Yellow Jacket
Globe M
Colorado Mine
Ralston Group
Dedrick
Maple Mine
Mason & Thayer Mine
Enterprise Mine
Lone Jack Mine
Yellowstone Mine
Ozark Mine
Gwin
Rich Gulch
Ratrick Gulch
Weaver Bally Mtn
Old Hill Mine
Hobo Gulch Camp
Big Branch
Logan Gulch
Rabbit Creek
Bay Horse Creek
Rattlesnake Creek
French Gulch
Gas Creek
Whites Creek
Ripstein Gulch
Canyon
Lena
Mountain View
Willow Creek 38 mi
Big Bar 53 mi
Junction City 10 mi
Weaverville 6 mi
LIMESTONE RIDGE
TWIN SISTERS FAULT
BACKBONE RIDGE
EAST FORK FAULT
NORTH FORK FAULT
TRELOAR RIDGE
CANYON RIDGE
A
A'
B
B'
Qg
Qm
Jd
Jt
sp
db
gb
hg
spd
udp
ssch
lPPc
lPPm
lPPq
N

The area has an average relief of about 4,000 feet. Thompson Peak, the highest point, rises to 9,000 feet on the north edge of the quadrangle. The Trinity River flows across the southern border at an elevation of about 1,500 feet. Stream dissection is complete, and remnants of old gravel and bedrock terraces form the only nearly level surfaces. Annual precipitation is about 40 inches, and streams and springs are abundant although their flow decreases markedly in the dry, late summer months. The vegetation is heavy: north slopes carry a deep soil and vigorous growth of fir, pine, and locally cedar; south slopes are blanketed by brush, chiefly manzanita and various members of the sumac family. Digger pines and live oaks are abundant at lower elevations.

Reconnaissance mapping was done during five months in the summers of 1954 and 1955. Geology was plotted on the USGS topographic Helena quadrangle map at a scale of 1:62,500, and extensive use was made of aerial photographs in plotting contacts shown by vegetation changes. Some areas were not reached because of heavy brush and shortage of time; they are the main courses of Manzanita Creek, Big French Creek, and Gas Creek and the upper courses of the following streams: Thurston Gulch, East Branch of East Fork of Trinity River, Yellow Jacket Creek, Ripstein Gulch, Gwin Gulch, and Rarick Gulch.

The Stanford faculty, particularly Dr. C. F. Park and Dr. C. O. Hutton, were most helpful in preparation of the PhD dissertation on which this report is based. W. P. Irwin and D. B. Tatlock of the U.S. Geological Survey offered advice and assistance in the field. The Shell Foundation and Dr. A. W. Pinger provided financial assistance. Great thanks is due to W. K. Graham of Palo Alto who served as my invaluable field assistant. The U.S. Forest Service and the residents of the area cooperated freely in making this work possible.

GENERAL GEOLOGY

The Helena quadrangle is underlain by four major rock units in contact with each other along north-trending, east-dipping reverse faults. From east to west these units are 1) The Salmon Hornblende Schist of pre-Permian age, 2) Metasedimentary rocks consisting of metachert, slate, marble, and greenstone probably of Late Pennsylvanian or Permian age, 3) Diabase, serpentine, gabbro, and diorite forming the mafic complex of Limestone Ridge, and 4) Amphibolite, actinolite schist, and related rocks forming the mafic complex of Logan Gulch.

Salmon Hornblende Schist is thrust over the metasedimentary rocks along the East Fork fault. The metasedimentary rocks lie in two areas separated by a fault block containing the mafic complex of Limestone Ridge. Both the metasedimentary rocks and the mafic complex of Limestone Ridge appear to be thrust over the mafic complex of Logan Gulch, the latter complex being exposed in a window in the canyon of the Trinity River.

Tonalite and diorite stocks and minor dike rocks intrude all the units except the mafic complex of Logan Gulch. The stocks also cut two of the major faults. They are part of a widespread system of stocks dated as Late Jurassic (Hinds, 1934, p. 184–182; Irwin, 1960, p. 57–58).

The Salmon Hornblende Schist is a major unit of the central metamorphic belt (Irwin, 1960, p. 18–20) of the Klamath Mountains. This belt extends in an arc from the Cretaceous overlap west of Redding to Yreka. The metasedimentary rocks and the two mafic complexes lie within Irwin's (1960, p. 15) western Paleozoic and Triassic belt. Recent workers (Lanphere and Irwin, 1965; Davis, et al., 1965; and Davis, 1965) have presented evidence for the following tectonic history for the region: Major orogeny occurred during the Carboniferous forming the central metamorphic belt. This was followed by thrusting of the metamorphic belt over the western Paleozoic and Triassic belt in Permian or Triassic time. Widespread intrusion of tonalite occurred in Late Jurassic or Early Cretaceous time followed by regional uplift during the Cretaceous and Tertiary.

Alpine glaciation has been a major factor in forming the topography of the northern part of the quadrangle. Many cirques, tarn lakes, and U-shaped valleys are present in the Trinity Alps, and small cirques were noted in the Thurston Peaks and Pony Mountain areas. Deeply weathered morainal deposits occupy the valleys of Canyon Creek, Rattlesnake Creek, and the heads of Whites Creek and East Fork of Trinity River.

Stream gravels are found on numerous rock terraces along Canyon Creek and the Trinity River. These gravels are auriferous and many deposits have been worked by hydraulic mining.

DESCRIPTION OF THE ROCKS [1]

Salmon Hornblende Schist

General. The eastern half of the quadrangle is underlain by the Salmon Hornblende Schist. This unit is in contact with the metasedimentary rocks along the East Fork fault and extends north, east, and south beyond the limits of the quadrangle. Hershey (1901, p. 229) named this unit after its exposures on the "south fork of the Salmon River between its head and the vicinity of the village of Cecilville" (see fig. 1).

Description. Three varieties of Salmon Hornblende Schist were noted in the area. Medium-grained hornblende-oligoclase-clinozoisite schist is the most common variety. It is well exposed along the lower course of Canyon Creek and extends over the major part of the quadrangle. The second type is a migmatized variety of the first with the addition of quartz and albite in thin laminae or more rarely in 6-inch pods. This rock crops out sporadically along the schist-tonalite contacts and near Weaver Bally Mountain along the eastern border of the quadrangle. The third variety is a finer-grained albite-epidote-actinolite schist found along a band up to 300 yards wide adjacent to the East Fork fault. Contacts between these rock types are gradational.

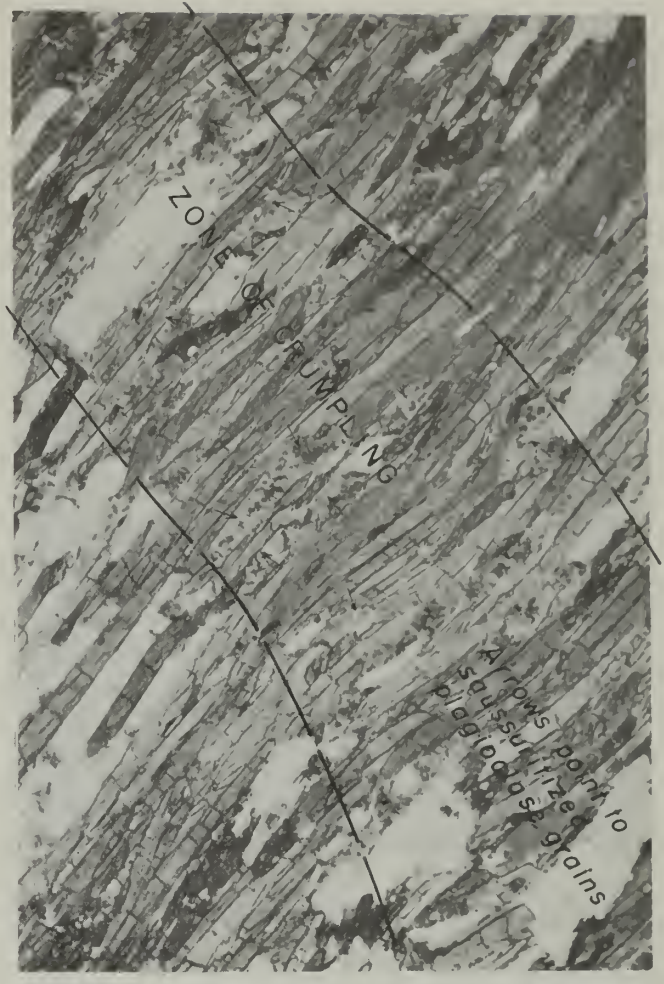
[1] For detailed petrographic descriptions see Cox, D. P., 1956, Geology of the Helena quadrangle, Trinity County, California: Ph.D. dissertation, Stanford University.

The common variety of hornblende schist is a homogeneous lustrous, black, medium grained rock in which amphibole is the predominant visible mineral. The amphibole always shows a strong lineation which, however, may be strongly distorted by later crumpling. Commonly one or more foliation planes are superimposed on this lineation. More rarely, thin alternating amphibole-rich and plagioclase-rich layers give the rock a gneissic foliation and when these bands are abundant, the rock passes into the migmatized variety. Closely spaced, slickensided and chloritized surfaces may occur in the rock as along Highway 299 west of Junction City and along East Fork of North Fork Trinity River.

In thin section the common variety of schist is seen to be composed of 60% to 70% hornblende (pleochroic with X light green and Z smoky blue green), 20% to 30% oligoclase (An_{10-20}), and up to 15% clinozoisite in discrete crystals. Accessory minerals are apatite, sphene, rutile, and magnetite. The anorthite content of the plagioclase varies inversely with the content of clinozoisite. Retrograde formation of saussurite (very fine-grained, cloudy patches of albite and epidote) at the expense of plagioclase in the axial planes of crumples and microfolds is notable in these rocks (photo 1). Late formation of lime silicate minerals, notably pumpellyite at the expense of the plagioclase, is more intense in the migmatized zones.

In the fine-grained schist found along the lower course of East Fork of North Fork, plagioclase is slightly more sodic and the amphibole is fibrous, pale green, and not detectably pleochroic. Plagioclase is segregated into small patches surrounded by fibrous amphibole, and opaque iron and titanium minerals are concentrated in dusty masses throughout the rock. Chlorite, calcite, and green porphyroblastic epidote are abundant. Locally these minerals constitute the major part of the rock forming chlorite schist, calcite-actinolite schist, and epidosite. The fine, patchy texture and the variability of mineral composition of these rocks suggests that they are the product of retrograde metamorphism of the Salmon Hornblende Schist. Their position adjacent to the East Fork fault suggests that fracturing and introduction of fluids along the fault were the chief factors in their formation.

Age of metamorphism. Metamorphism of the Salmon Hornblende Schist almost certainly predates the main Nevadan Orogeny during which most of the major faults and granitic stocks were formed. Potassium-argon dating gives an age of 270–286 million years (Pennsylvanian) for hornblende in the Salmon Hornblende Schist (M. A. Lanphere and W. P. Irwin, 1965), Program, Geol. Soc. America Cordilleran Sec. Mtg., Fresno, California, p. 33). Moreover, the dominant east-west trend of hornblende lineation shown on the geologic map suggests that metamorphism took place under stress orientations unrelated to those of the Nevadan orogeny which formed the northwest trend typical of this portion of the Klamath Mountains. Finally, retrograde metamorphism of amphibolite to chlorite-actinolite schist along the East Fork fault indicates that the amphibolite facies metamorphism predated this fault as well as the tonalite intrusions which cut the fault.



Phato 1. Photomicrograph of hornblende schist shawing saussuritization of plogioclase along crumple. Ploin light, 20 ×.

Metasedimentary rocks

Age and correlation. Metachert, slate, and subordinate marble, greenstone, and quartzite crop out on Backbone Ridge and in the southwest part of the quadrangle. These two areas of exposure are separated by a large fault-block of diabase and gabbro. The metachert of the Backbone Ridge area is in fault contact with the Salmon Hornblende Schist along the East Fork fault on the east side and extends westward about 15 miles beyond the limits of the quadrangle.

These rocks were referred to as the Lower Slate Series by Hershey (1901) and later by Diller (1903) as the Southwestern Carboniferous Belt. They were described by both authors as extending from Harrison Gulch in Shasta County through Hall City, Bridge Creek, Hayfork Valley, the lower Trinity Basin, and

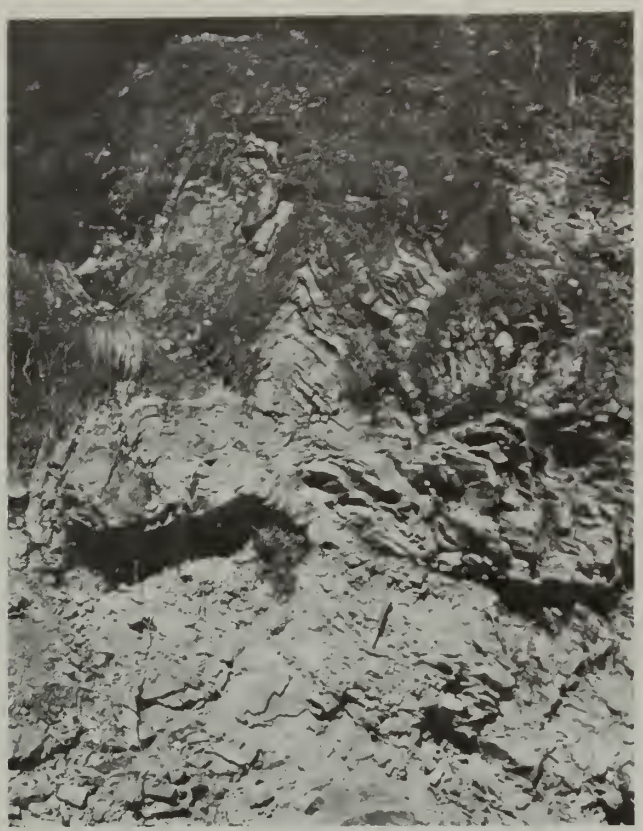


Photo 2. Tight folding in thin-bedded metochert.

across the divide to the New River. Irwin (1960, p. 15) included these rocks with others farther to the west and applied the informal name western Paleozoic and Triassic belt. Hinds (1932, p. 392) applied the name Chanchelulla Formation to these rocks based on their exposures on the slopes of Chanchelulla Peak. Because of the inexactness of Hinds' type locality, it is deemed advisable not to continue the use of this name. Irwin (1963) used the term "sedimentary and volcanic rocks" for a unit in the southwest part of the Weaverville quadrangle which lies in the same relation to the East Fork fault. Davis and Lipman (1962, p. 1549) have suggested a correlation of the metasedimentary rocks in the Helena quadrangle with the more highly metamorphosed Stuart Fork Formation in the Trinity Lake quadrangle.

No fossils were found in the Helena quadrangle owing to the degree of deformation of the metasedimentary rocks. A few fossils have been found to the south and west within the western Paleozoic and Triassic belt, those found on the east side of the belt being Late Pennsylvanian or Permian in age (Irwin, 1960, p. 26). Irwin found fusulinids of this age near the west edge of the Hayfork quadrangle in float, presumably derived from limestone beds in the same structural position as those on Backbone Ridge. On this basis a Permian-Late Pennsylvanian age is tentatively assigned to the metasedimentary rocks in the Helena quadrangle.

Metachert and slate. Thin-bedded chert with thin slaty partings makes up about 80% of the exposed portion of the metasedimentary unit. The chert is generally dark gray and forms beds one-eighth inch to four inches thick separated by thinner beds of slate or fissile chert containing abundant, very fine-grained mica. Within any one outcrop the beds are of nearly equal thickness. Very commonly this bedding shows complex convolutions with folds faulted against other folds (photo 2). The fold axes are usually horizontal and parallel to the general trend of the bedding but show no consistent direction of overturning. Closely spaced joints are common in the folded chert beds and are oriented perpendicular to the fold axes.

In thin section the metachert is seen to be weakly recrystallized. A distinct preferred orientation of the minute quartz grains can usually be demonstrated with the gypsum plate. Very fine, pale yellow to greenish flakes of mica are common in both chert and interbedded slate. Small, round, clear spots, probably remnants of radiolarian tests, are abundant in the chert.

Subordinate rocks. Marble, greenstone, and quartzite make up from ten to twenty percent of the metasedimentary unit. The marble is found in beds 5 to 20 feet thick and less commonly in lenses 200 to 700 feet thick throughout the unit. These bodies are in general limited in strike length to approximately 1000 feet, but a lens nearly 2 miles long crops out in the southwest part of the quadrangle. The marble is massive and shows no primary sedimentary structures or textures. The marble is bluish gray and gives off a fetid odor when fractured. It is composed of coarse calcite grains many of which have a distinct preferred orientation.

Deeply weathered greenstone is exposed in at least three places in cuts along the road between Helena and Hobo Gulch. The rock is deeply weathered and iron stained and its mineral content is obscured; however, patterns in the outcrops suggesting pillow structure are common and indicate a marine volcanic origin for these rocks.

One exposure of quartzite on Manzanita Ridge was noted. This rock contains quartz, minor feldspar, and chert fragments in a matrix of fine muscovite and chlorite. The quartz grains are one to two millimeters in diameter.

Metamorphism. Incipient recrystallization forming mineral assemblages of the greenschist facies of regional metamorphism is characteristic of all rocks of the metasedimentary unit. Exposures of this unit in East Fork of North Fork contain coarse muscovite in contorted aggregates as well as coarse-grained quartz in veins and contorted laminations. Penetrative rock deformation and possibly more abundant fluids near the East Fork fault probably facilitated the growth of these mineral grains.

Muscovite gives way to biotite in metacherts near the contact with the mafic complex of Logan Gulch. This increase in metamorphic grade is thought to be caused by movement on a thrust fault which bounds the complex and by increased temperature possibly related to igneous intrusives within the complex.

afic complex of Limestone Ridge

General. A large north-trending block of diabase in ault contact with the metasedimentary rocks on the ast and west occupies most of Limestone Ridge. (The ame "Limestone Ridge" derives from the fact that a 00-foot-thick bed of marble belonging to the meta-edimentary unit crops out on the northward extension f this ridge about one mile north of Cabin Peak.) Gabbro and serpentine intrude the diabase, and sheared erpentine occupies the fault zones bounding the block.

Diabase. The diabase is a medium to fine grained, ard, greenish-black rock in which plagioclase laths re distinct. The rock is uniform in texture and lacks low structure, bedding, or pillow structure through-ut the quadrangle area. Pillow structure is abundantly leveloped in these rocks, however, to the northwest f the quadrangle along the East Fork of New River. Shear zones along which the diabase is crushed and chloritized strike northwest across the block.

In thin section the diabase is seen to be composed chiefly of augite and plagioclase. The texture is diabasic to ophitic and the grain size ranges from 0.2 to 1.0 millimeter. Rarely the diabase is porphyritic with small phenocrysts of plagioclase and augite. The augite is colorless and commonly altered to pale uralitic amphibole or chlorite. The plagioclase varies in composition from An_5 to An_{40} and is partly altered to epidote. Epidote is present in dusty patches of saussurite (microcrystalline albite and epidote) and also may occur with prehnite in veinlets. Magnetite and ilmenite occur as small skeletal crystals and also form dusty patches associated with the development of uralite.

Gabbro. More or less altered gabbro crops out in a discontinuous band along the east side of the mafic complex and extends into the Hayfork quadrangle to the south. The rock is dark gray when unmetamorphosed but almost everywhere contains white patches of saussurite in the plagioclase (photo 3). The rock is composed mainly of augite and labradorite-bytownite, minor magnetite, and dark red-brown spinel and is commonly altered to hard, chalky-white saussurite with bronze, pseudomicaceous grains of diallage. The altered gabbro is commonly cut by veinlets of chrysotile or colorless chlorite.

Hornblende diorite intrusions of irregular shape occur with the gabbro on Limestone Ridge. The diorite is highly variable in composition but generally contains brown hornblende as reaction rims around small cores of augite; plagioclase ranging from albite to andesine; and minor quartz which forms myrmekitic intergrowths with plagioclase. The close association of the hornblende diorite with the gabbro and its myrmekitic texture suggest that it is a late differentiate from the gabbro, comparatively richer in silica and volatiles.

Serpentinite. Massive black serpentinite crops out in two areas in the northwestern part of the quadrangle. It is composed of antigorite, chrysotile, minor talc, and relic enstatite. Mesh structure formed by alignment of dusty opaque minerals and bastite structure

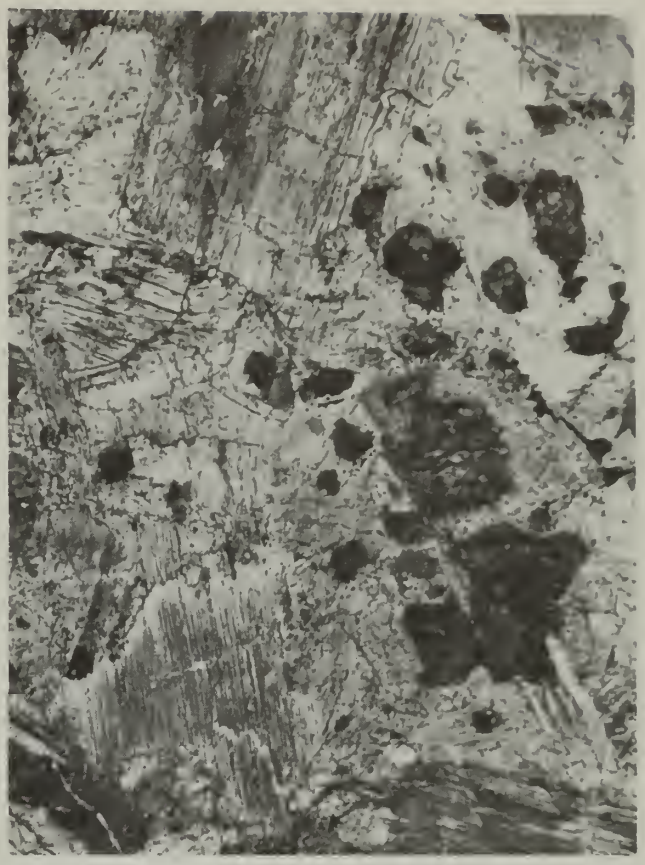


Photo 3. Photomicrograph of gabbro showing parting in diallage and patches of saussurite (dark areas) in plagioclase. Crossed nicols, 30 ×.

attest to the coarse-grained texture of the original peridotite. Chromite occurs as disseminated grains and small stringers east of Whites Creek Lake.

Sheared green serpentinite forms a long dike-like body following the North Fork fault and is dispersed in small stringers through diabase along the Twin Sisters fault and along other shear zones in the mafic complex. This serpentine is schistose and displays no relict igneous structures.

Mafic complex of Logan Gulch

General. Mafic igneous rocks which are for the most part metamorphosed to the amphibolite facies are exposed along the Trinity River west of Helena and in the lower courses of Wheel Gulch, Cutthroat Gulch, and Logan Gulch. These rocks will be referred to in this paper as the mafic complex of Logan Gulch.

The principal rock type in this area is actinolite schist probably derived from volcanic rocks of andesitic to basaltic composition. This rock is quite uniform in composition and everywhere contains relict euhedral pyroxene and amphibole crystals one to three millimeters in diameter. Since euhedral pyroxene is rare in gabbroic or diabasic intrusive rocks in this area, this rock is believed to be of volcanic origin. Layered amphibolite containing the same euhedral ferro-magnesian grains is the second most abundant rock type of the complex. This rock is well exposed in the bed of the Trinity River west of Cutthroat

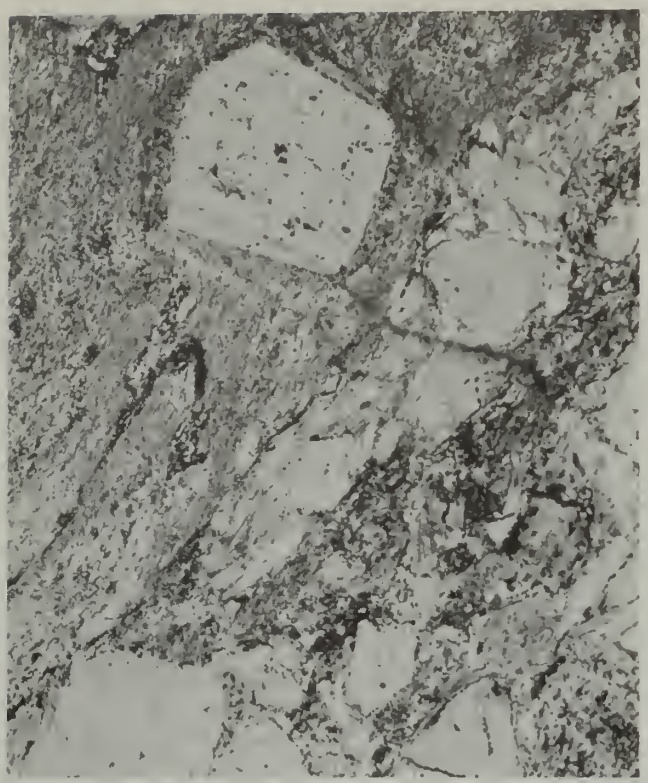


Photo 4. Photomicrograph of actinolite schist showing euhedrol relict phenocryst. Plain light, 22 ×.

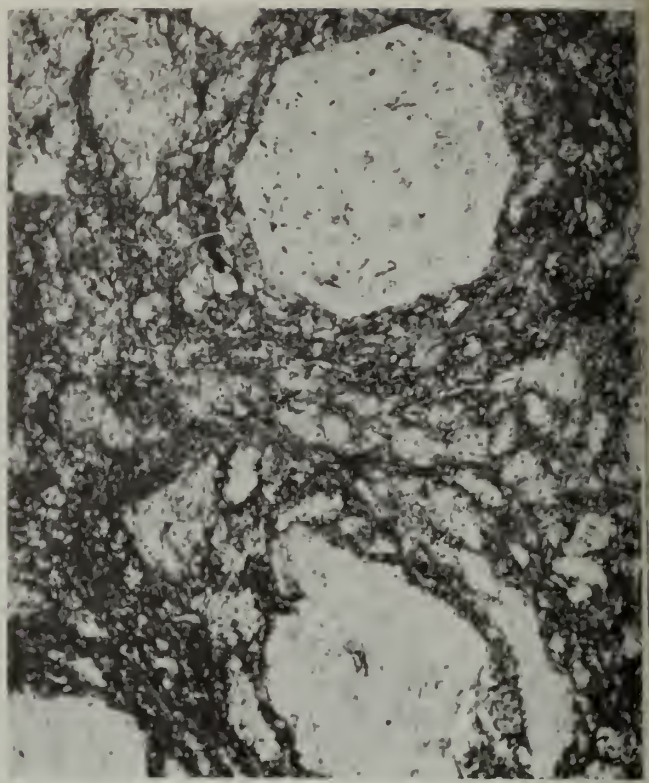


Photo 5. Photomicrograph of actinolite schist showing alignment of plagioclase grains around euhedrol relict phenocrysts. Plain light, 22 ×.

Gulch and continues to the west boundary of the complex near Big Flat public campground in the Hayfork quadrangle.

Garnet amphibolite gneiss and massive hornblendite are exposed in a small area near the bend of the Trinity River 0.4 mile west of the mouth of North Fork. A small body of pyroxenite is exposed near the mouth of Wheel Gulch in the Hayfork quadrangle.

Structural relations. The contacts of the mafic complex on the upper slopes of the Trinity River canyon are not well exposed and the structural relations between the complex and the metasedimentary rocks have not been clearly established. However, the general configuration of the map unit, the nature of the rocks along the contact, and the sharp increase in metamorphic grade at the contact all suggest that the complex is exposed in a window in a low angle thrust fault lying beneath the Twin Sisters fault.

Actinolite schist. In hand specimen these rocks show strong lineation produced by intersection of irregular slip surfaces, but planar schistosity is not pronounced. Closely spaced, euhedral phenocrysts with lustrous cleavage faces are abundant. In thin section (photo 4) these phenocrysts prove to be composed of fibrous uralitic amphibole, some crystals having unreplaced cores of augite. Faint traces of original plagioclase are visible in the mass of fine actinolite and clinozoisite that makes up the matrix of the rock. The plagioclase relicts and the actinolite are aligned around the phenocrysts in a fluidal texture (photo 5). Calcite is locally abundant and quartz is localized in pressure shadows around the uralite crystals.

The lineation produced by alignment of actinolite grains and by the intersection of irregular slip surfaces plunges 5 to 20 degrees in a direction S. 60° E. to S. 80° E.

Layered amphibolite. This rock is black with prominent greenish-gray to white layers one to ten millimeters in thickness (photo 6). The euhedral

Photo 6. Fine, dark, and light layers in layered amphibolite.

ferromagnesian grains common to the actinolite schist are abundant throughout this rock. The black portion of the rock is composed of green hornblende and andesine (photo 7). The relict phenocrysts in the black portion are pale uralitic amphibole probably derived from pyroxene, and brown hornblende probably of igneous origin. Both types of phenocrysts show overgrowths of green hornblende. The white and gray bands are so fine grained as to appear nearly opaque in thin section (photo 8). No determination of the composition of the matrix was possible with a microscope. Discontinuous stringers of quartz, hornblende and fine plagioclase run through the fine material and bend around the euhedral relict phenocrysts. The uralitized phenocrysts in the white layers contain prominent cores of augite.

The white and gray layers of the amphibolite strike generally northwest and dip eastward 5 to 45 degrees. They may extend several meters along strike and, in places, they are continuous with augen of metavolcanic rock. The white layers are thought to be mylonite formed by crushing of a porphyritic volcanic rock. The matrix of the rock yielded to crushing first, and the phenocrysts were rolled but not destroyed. The presence of unaltered cores of augite in the relict phenocrysts in the white, fine-grained layers suggests that the layers are not derived by mylonitization of the surrounding amphibolite, in which unreplaced augite is lacking. The white layers must then be remnants of the earlier volcanic rock, ground to powder but somehow escaping recrystallization to amphibolite. A detailed study of these rocks is necessary before the origin of the banding can be fully explained.

Instrusive rocks. The mafic complex of Logan Gulch includes a small mass of hornblendite at its eastern extremity and a somewhat larger body of clinopyroxenite at its western contact outside the Helena quadrangle. The hornblendite appears to have been emplaced during the metamorphism of the surrounding rocks since its contacts are sheared and grade into schists of the mafic complex. The clinopyroxenite is unaltered and in sharp contact with the surrounding amphibolites.

The hornblendite occurs in a dike 1,000 to 1,500 feet by 100 to 300 feet striking N 60° W. The rock is composed almost entirely of 1 to 2 centimeter subhedral grains of hornblende. The hornblende is pale brownish green with $2V = 85°$ and Z to $C = 23°$. It is mottled by alteration to a very pale green amphibole. Prehnite, saussurite, coarse zoisite and calcite make up 20 percent of the rock.

The hornblendite body is bordered by fine-grained granular amphibolite and by hornblende plagioclase biotite almandine-gneiss. The hornblende in the gneiss is twinned and is similar in optical properties to the hornblende in the hornblendite dike. The plagioclase shows polysynthetic twinning and normal zoning from An_{43} to An_{27}. Color and twinning of the hornblende and twinning and zoning of the plagioclase indicate that these minerals are stable relict magmatic minerals derived from an igneous rock probably once part of the hornblendite. Strong deformation at magmatic temperature during the intrusion of these rocks produced a metamorphic environment in which the igneous hornblende and plagioclase were stable and in which new almandine and biotite were formed.

Clinopyroxenite crops out in Wheel Gulch near the Trinity River. It is composed of one-centimeter, interlocking grains of augite with very small amounts of chlorite and actinolite.

Metamorphism. Mineral assemblages andesine-hornblende and actinolite-oligoclase-epidote fall within the amphibolite facies of regional metamorphism and show the distinctly higher grade of metamorphism of

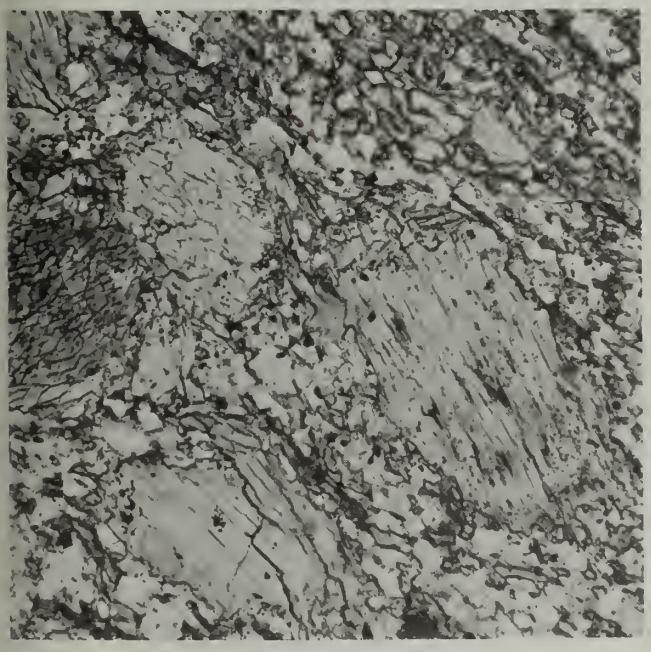


Photo 7. Photomicrograph of dark layer in layered amphibolite. Plain light, 60 ×.

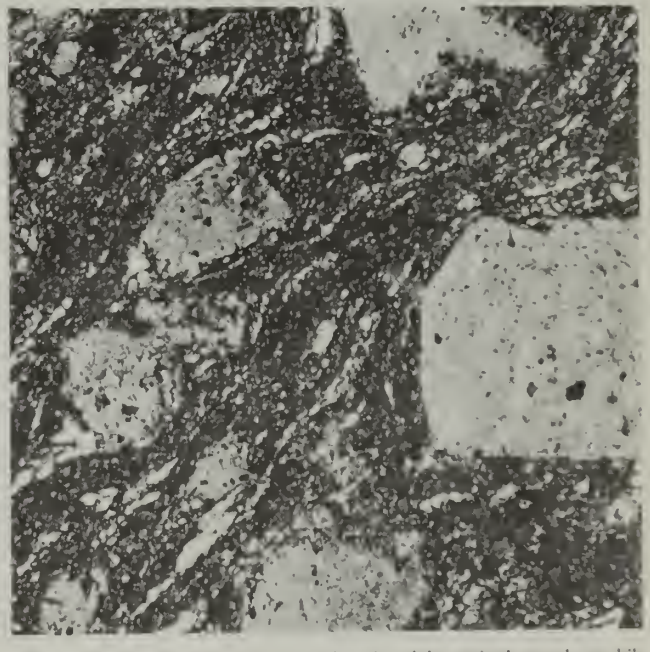


Photo 8. Photomicrograph of light-colored layer in layered amphibolite showing euhedral relict phenocrysts of uralitized augite. Plain light, 60 ×.

Photo 9. Aeriol photograph showing tonolite (1), omphibolite (2), and west contoct of Conyon Creek stock (3).

hese rocks as compared with the surrounding meta-
edimentary rocks. The age of this metamorphism is
nknown but formation of biotite in the metasedi-
nentary rocks adjacent to the complex suggests that
he metamorphism was in part contemporaneous with
he thrusting of the metasedimentary rocks over the
omplex. Intrusion of hornblendite may have occurred
uring this thrusting and supplied some heat.

onalite and diorite intrusions

General. Tonalite of the Canyon Creek stock occu-
ies the northeast corner of the quadrangle. A portion
f another large stock crops out along the east edge
f the quadrangle. Small stocks of altered tonalite
rop out near East Fork Creek and dikes or lenses
ntrude the East Fork fault zone near the Trinity
River. Three small stocks of hornblende diorite were
oted in the northern part of the area.

Canyon Creek stock. The Canyon Creek stock is
composed of plagioclase (andesine-labradorite with
outer zones of oligoclase), 55%; quartz, 25% to 30%;
nd equal amounts of biotite and hornblende together
making up 10% to 20%. Near the contact, biotite
nd hornblende content increases and quartz content
decreases within the stated ranges. Trace amounts of
perthite are found near the central part of the stock.
Apatite, sphene, and magnetite are accessory minerals.

Alignment of biotite parallel to the western contact
is very pronounced but becomes less so within the
central part of the stock. Lipman (1964) noted several
broad domes and basins defined by this alignment of
biotite, all trending northwest parallel to the structural
grain of the region.

The west contact of the stock is vertical and forms
a remarkably smooth curve from Thompson Peak to
Canyon Creek (photo 9). Migmatized amphibolite
with foliation parallel to the contact is present in a
zone 100 feet wide near the stock. In places tonalite
has congealed in the process of stoping large slabs of
amphibolite into the magma chamber. Vertically
oriented, discoidal inclusions of amphibolite are abun-
dant in the tonalite near the western contact (photo
10). Within the central part of the stock, amphibolite
inclusions are less abundant and are angular in shape.
Near Canyon Creek Lakes, swarms of discoidal inclu-
sions form sharply defined bands five to ten feet wide
and several hundred feet long. The inclusions are all
nearly the same size; they are parallel to one another;
and are separated by small amounts of tonalite.

Minor tonalite and diorite intrusions. A small pluton
1½ miles west of the Canyon Creek stock has a com-
position ranging from hornblende diorite to biotite
granodiorite in the inner part. The stock which under-
lies Cabin Peak on the north border of the area is
uniformly dioritic in composition, and the stock near
Hunters Camp is dioritic to gabbroic with roughly
equal proportions of labradorite-andesine and horn-
blende.

Tonalite associated with the East Fork fault has a
variable composition and is generally hydrothermally
altered. The stock south of the Enterprise mine has
an outer diorite zone containing abundant hornblende
and an inner quartz diorite zone. Epidote and musco-

Photo 10. Vertically oriented discoidal inclusions 100 feet from west contact of Canyon Creek stock.

vite are the major alteration products and in most of
the other small bodies completely replace the ferro-
magnesian minerals. The stocks in Barney Gulch are
altered entirely to quartz and muscovite.

Age. Davis and others (1965, p. 963) have sum-
marized the potassium-argon ages of biotites from five
Trinity Alps plutons. The plutons range from 125 to
140 million years, 133 million years being the age of
the Caribou Mountain stock three miles northwest of
the Helena quadrangle. No age determination is yet
available for the stocks within the quadrangle. Strati-
graphic evidence (Hinds, 1934, p. 184–192; Irwin,
1960, p. 57–58) indicates a Late Jurassic or Cretaceous
age for this group of rocks. The younger potassium-
argon ages probably represent the time of uplift and
cooling of the rocks rather than their actual intrusion.

Dike rocks

Lamprophyre and minor aplite dikes cut the Can-
yon Creek stock and dikes of andesitic and dacitic
composition are found in many places in the Helena
quadrangle. Lamprophyre dikes are composed of
euhedral hornblende phenocrysts in a panidiomorphic
groundmass of andesine-labradorite and hornblende.
Hornblende-plagioclase rocks with panidiomorphic
texture but lacking phenocrysts are very abundant
throughout the quadrangle. Less common are porphy-
ritic dikes of dacitic composition with phenocrysts of
andesine, quartz, hornblende, and biotite in an apha-
nitic groundmass.

STRUCTURE

The rock units described in the Helena quadrangle are structurally very complex. The Salmon Hornblende Schist has probably been deformed during two orogenic periods. The first period in late Paleozoic time gave rise to amphibolite facies metamorphism and a westerly trend of hornblende lineation. The second, probably related to the Nevadan orogeny, gave rise to major westward thrusting and greenschist facies metamorphism, and formed northwesterly striking crumples and slip planes in the Salmon Hornblende Schist. The metasedimentary rocks and the Limestone Ridge mafic complex were also weakly metamorphosed, crumpled, and sheared during the second period of deformation. Davis (1965, Program, Geol. Soc. America Ann. Mtg.: Kansas City, Missouri, p. 41) believes this second period is of Permian or Triassic age.

Amphibolite facies metamorphism in the mafic complex of Logan Gulch and adjacent metasedimentary rocks may be related to intrusions in that area. Northwest lineation formed by intersection of slip planes in these rocks suggests an affinity with Nevadan structures. Irregularly but gently dipping metamorphic layering in the amphibolites between Cutthroat Gulch and Big Flat was probably produced at the same time as the proposed thrust which separates the complex from the overlying metasedimentary rocks.

The tonalite-diorite stocks were emplaced in the Late Jurassic or Cretaceous and are structurally undisturbed. A tonalite stock cuts acros the East Fork fault and although the tonalite is sheared and strongly altered, its contacts are not detectably displaced by the fault.

The major faults in the quadrangle are described below in detail, from east to west.

The East Fork fault is exposed only in the Red Hill Placer Mine on the south side of the Trinity River. At this point a shear zone a few inches wide dipping 40° east separates crushed amphibolite from metasedimentary rocks. Elsewhere the fault was mapped by the difference in vegetation supported by amphibolite and metasedimentary bedrock. Dips were determined from the trace of the fault on the topography.

The North Fork fault is intruded along most of its length by sheared serpentine. Estimates of the dip based on the trace of the fault on the topography range from 35° to 50° east, being steeper in the southern part of the quadrangle.

The Twin Sisters fault is marked by a wide zone of mixed serpentine and diabase with lenticular fault slivers of metasedimentary rock. The fault dips from 40° to 50° east in most of the area, but in the portion of the zone exposed in the Trinity River Valley near Helena it flattens to 18°. The fault appears to steepen again in the higher elevations to the south of the valley. The Twin Sisters fault coverges in depth with the North Fork fault, and where these faults cross the deeply eroded valley of the Trinity River, the diabase band between them narrows to a few hundred feet and is strongly sheared. Near the small cemetery east of Helena, the band consists of chlorite-calcite schists containing augen of altered diabase.

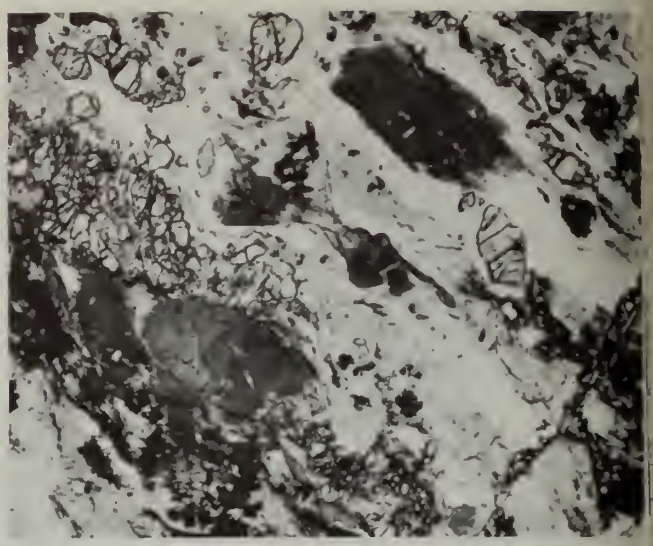


Photo 11. Photomicrograph of augen quartzite showing augen of chert in quartz-biotite matrix. Near Helena at contact with mafic complex of Logan Gulch. Plain light, 20 X.

Several lines of evidence indicate the presence of a thrust fault between the metasedimentary unit and the mafic complex of Logan Gulch. This fault would be the lowest of the series of faults exposed in the quadrangle. On the geologic map, the irregular outline of the complex and its elongation parallel to the Trinity River canyon suggest that the complex underlies the metasedimentary unit, having been exposed only in the deeper parts of the canyon. The mafic complex-metasedimentary rock contact appears to be a gently undulating surface rising from 1,200 feet elevation near Helena to 3,500 feet between Cutthroat Gulch and Wheel Gulch, then descending to the west. Dips in the metasedimentary rocks near the complex are generally steep and not conformable to this surface. Thus, the general configuration of the unit suggests a win-

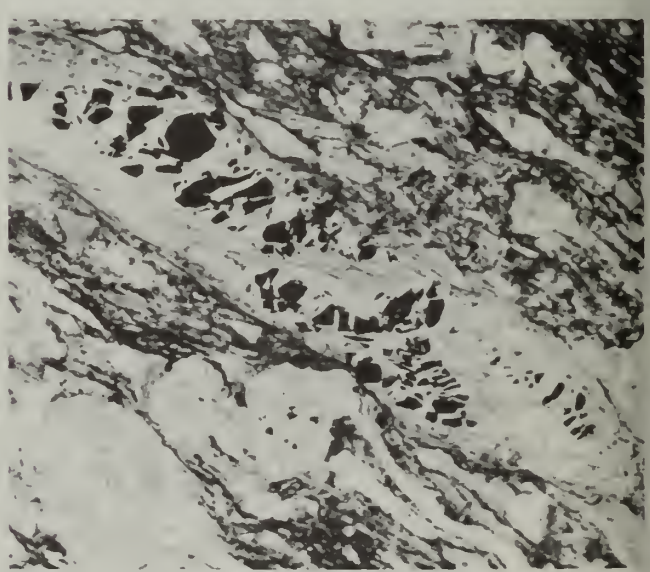


Photo 12. Photomicrograph of mixed augen schist in mafic complex of Logan Gulch near southeast contact. Augen are porphyritic volcanic rock, lower left; serpentine with chromite, center, and chert, not shown. Plain light, 20 X.

ow in a gently arched thrust fault cut by the deep anyon of the Trinity River. The arching of the fault rface coincides with the marked flattening of the win Sisters fault where it is exposed in the Trinity iver canyon.

The marked difference in metamorphic grade beween rocks of the metasedimentary unit and the mafic omplex also suggests a structural break between the wo units. Biotite is locally developed in metachert ear the contact with the mafic complex near Helena, ut elsewhere the metasedimentary unit is only weakly ltered. Rocks of the mafic complex, on the other and, contain metamorphic assemblages of actinolite-ligoclase-epidote or andesine-hornblende.

Two exposures of rocks near the contact of the omplex show many structures typical of fault zones. Near Helena, metachert becomes transformed to chert reccia, augen quartzite (photo 11), and finally to omogeneous biotite quartzite nearest to the contact. Outcrops of mixed-augen schist were found on Eagle Creek south of the Trinity River. This rock contains augen of chert, porphyritic volcanic rocks, and serpentine containing fractured grains of chromite (photo 12). Serpentine was not noted elsewhere in the complex. The small amount of matrix between these augen is composed of actinolite and chlorite.

ECONOMIC GEOLOGY

Gold occurs in quartz veins in the Salmon Hornblende Schist in the Dedrick district east of Dedrick along the east quadrangle boundary; in the East Fork district along the east side of the East Fork fault in the south central part of the quadrangle, and in the upper reaches of East Branch of East Fork and Yellow Jacket Creek. The veins are composed of white quartz and minor calcite and contain less than 1% pyrite, chalcopyrite, and galena. Ribbon structure is locally well developed. Alteration of enclosing hornblende schist to chlorite-calcite-pyrite schist is common.

Gold-bearing terrace gravels 50 to 75 feet thick along Canyon Creek and in the Trinity River valley have been mined by hydraulic methods and by dredging, mainly during the 1930's. Complete descriptions of the lode and placer mines in the area may be obtained in O'Brien (1965), Averill (1941), and Ferguson (1914).

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